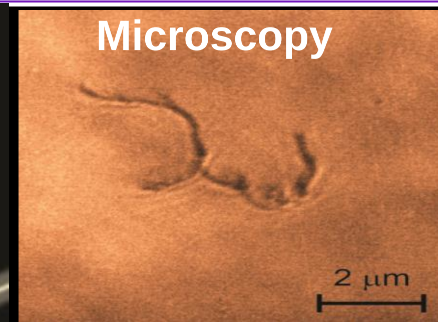
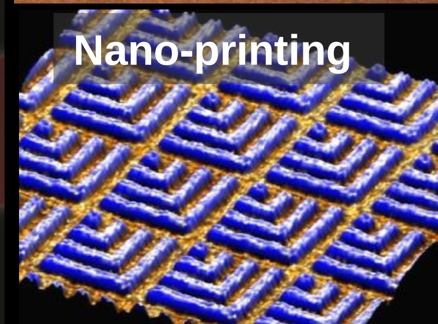
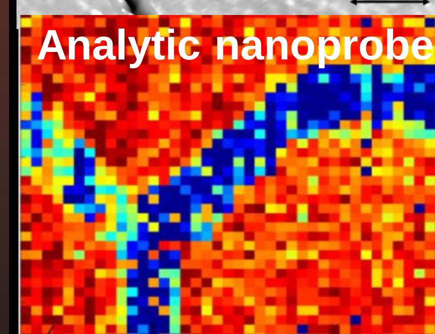
High repetition rate table-top soft x-ray lasers

Jorge J. Rocca, B. Reagan, Y. Wang, D. Alessi, B. Luther, K. Wernsing, L. Yin, M. Curtis, M. Berrill, D. Martz, V. Shlyaptsev, S. Wang, F. Furch, M. Woolstron, D. Patel, M.C. Marconi, C.S. Menoni

NSF Engineering Research Center for Extreme Ultraviolet Science & Technology
Colorado State University

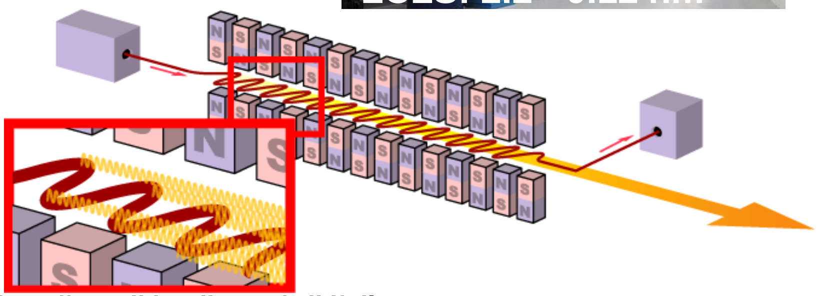




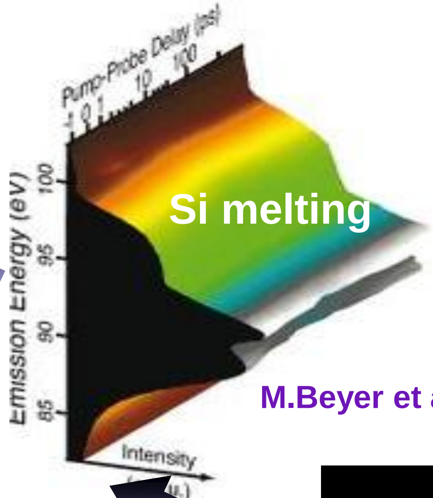


Work Supported by the NSF Engineering Research Centers Program and the US Department of Energy

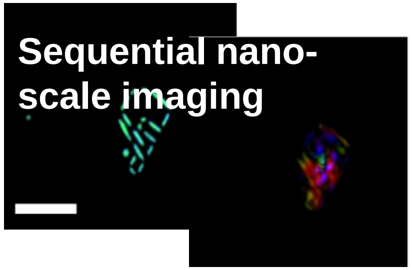
High interest in intense Coherent SXR light



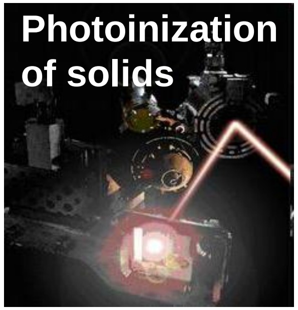
http://en.wikipedia.org/wiki/File:FEL.png



M.Beyer et al. PNAC, (2010)

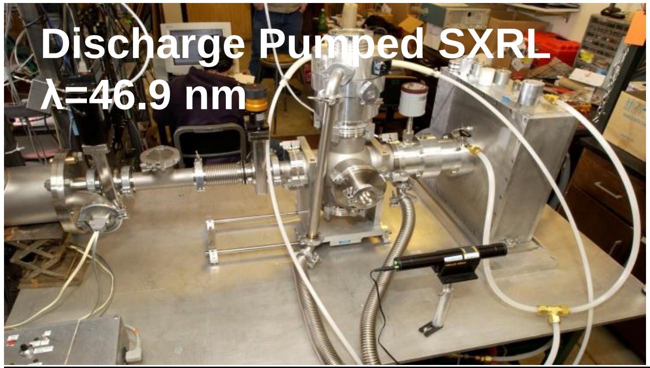


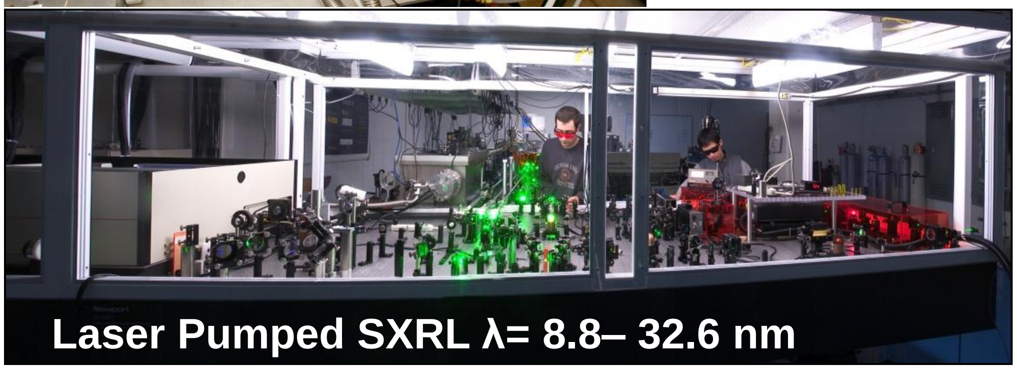
A. Barty et al. Nat. Phot., (2008)

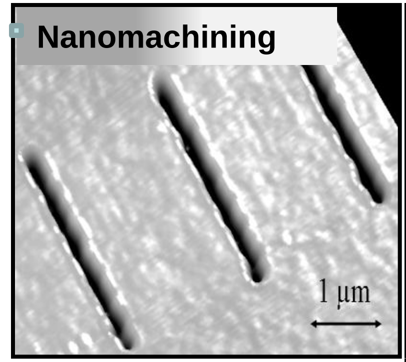


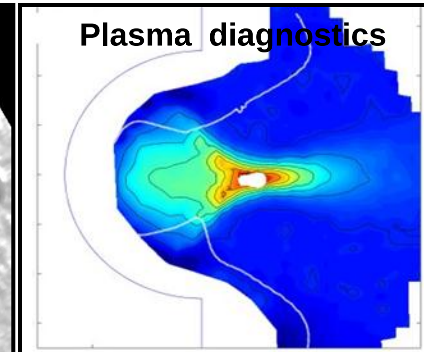
Nagler et al. Nat. Phys. (2011)

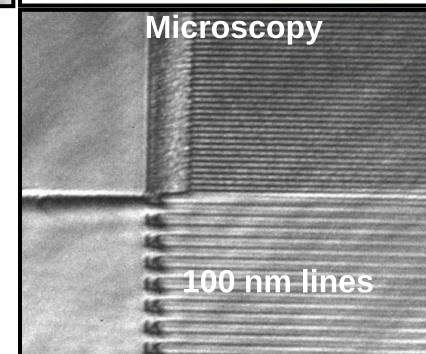
Compact plasma-based soft x-ray lasers can be installed at the application's site

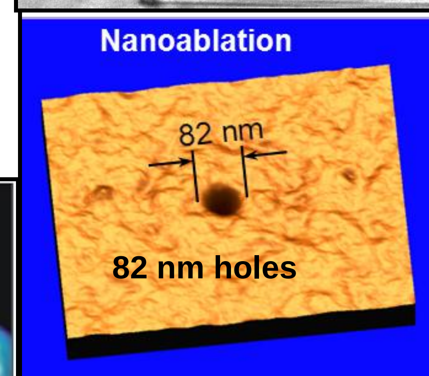




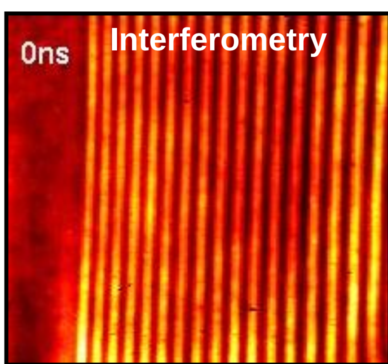


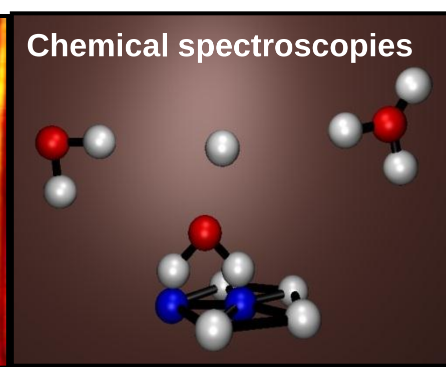


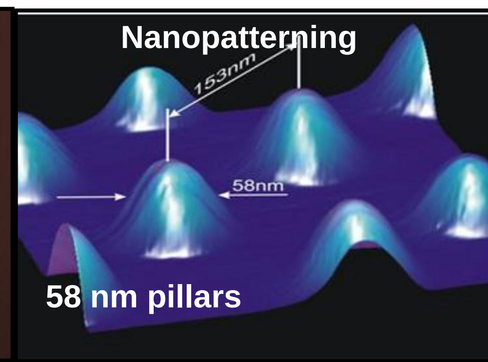




- High pulse energy (μJ-mJ)
- High monochromaticity ($\lambda/\Delta\lambda < 10^{-4}$)
- High peak spectral brightness

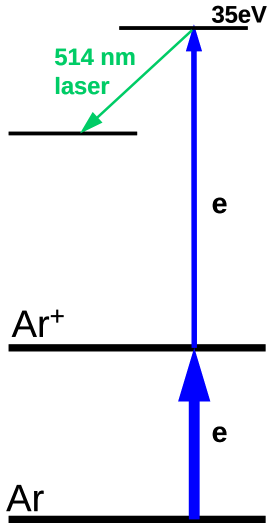






Soft x-ray lasers can be created by electron impact excitation of highly ionized atoms in dense plasmas

Singly ionized Ar ion, Kr ion lasers in the visible spectral region



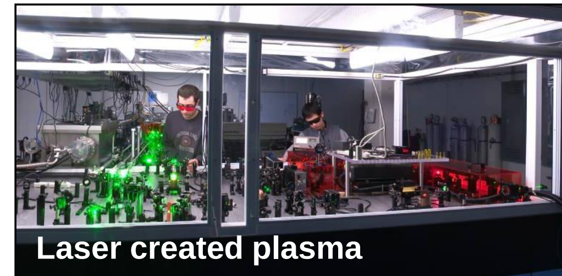
Plasma requirements:
Te ~ 5 eV
Ne ~ 1 10 ^{14} cm^{-3}

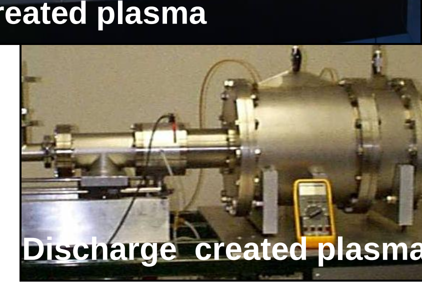
$$h\nu = \Delta E \propto Z^{2.5}$$

NexTe increases by 10^{7}-10^{10}

Te ~ 100- 1000 eV
Ne ~ 1 10 ^{19} - 1 10 ^{21} cm^{-3}

Highly ionized (8-35 times) in the EUV/SXR spectral region





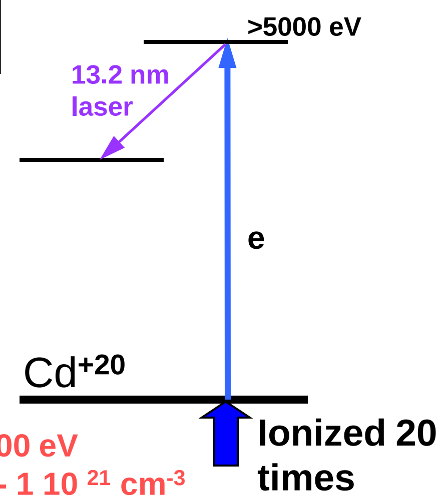
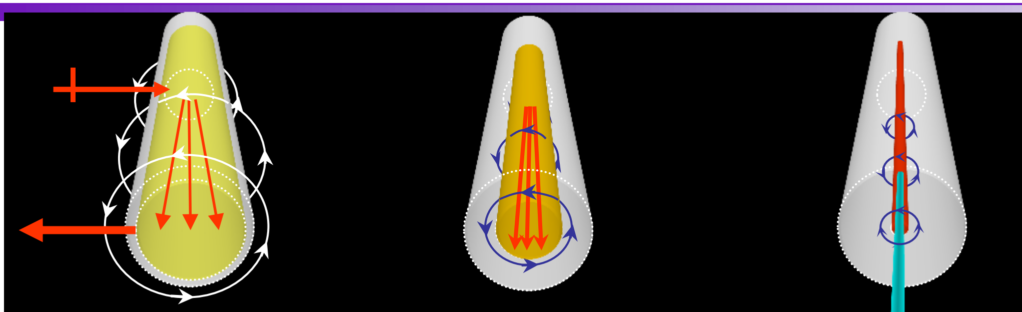
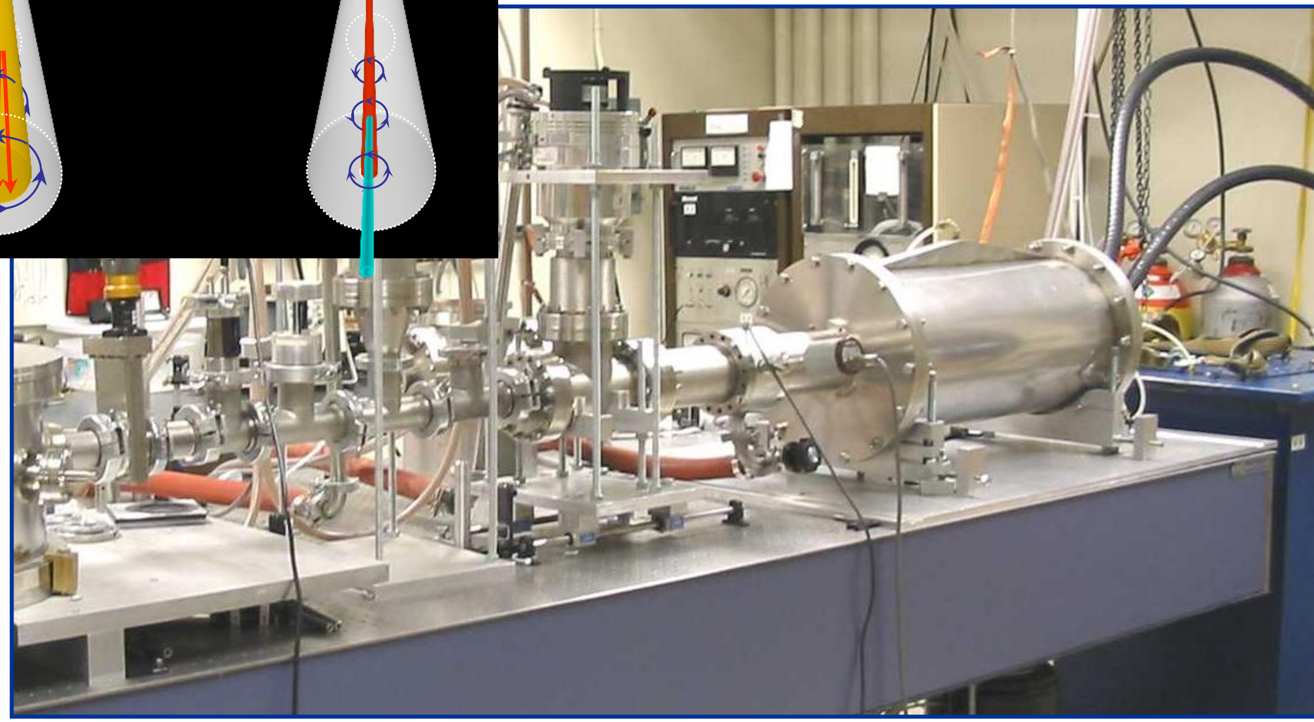


Table-top laser in Ne-like Ar produces coherent average power at λ=46.9 nm similar to synchrotron beam line





Ne-like Ar Capillary discharge 46.9 nm laser

High average power: up to 3 mW

High pulse energy: 0.1 mJ - 0.8 mJ @4 Hz

Narrow spectral bandwidth: $\Delta\lambda/\lambda$= 3 x10^{-5}

Beam divergence: θ = 4.5 mrad

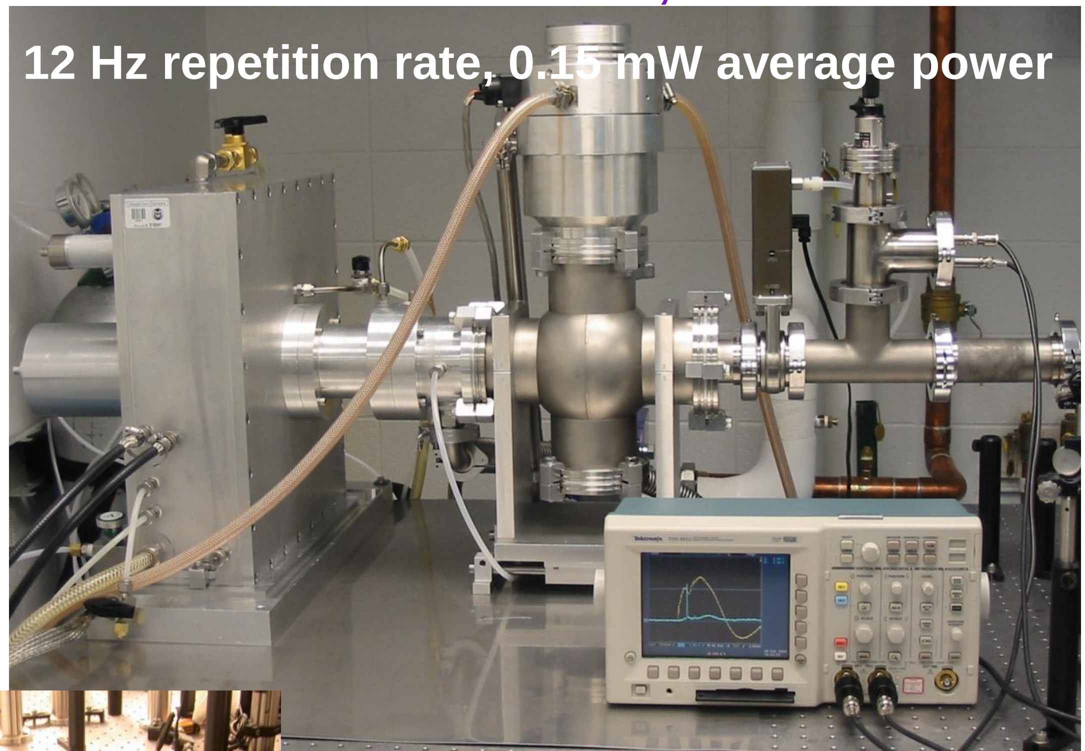
B. Benware et al. Phys.Rev.Lett, 81, 5804, (1998) ; C. Macchietto Opt. Lett 24, 1115, (1999)

Recent research has shrunk capillary discharge SXRL to desk-top size

EUV
An NSF Engineering Research Center

Colorado State University

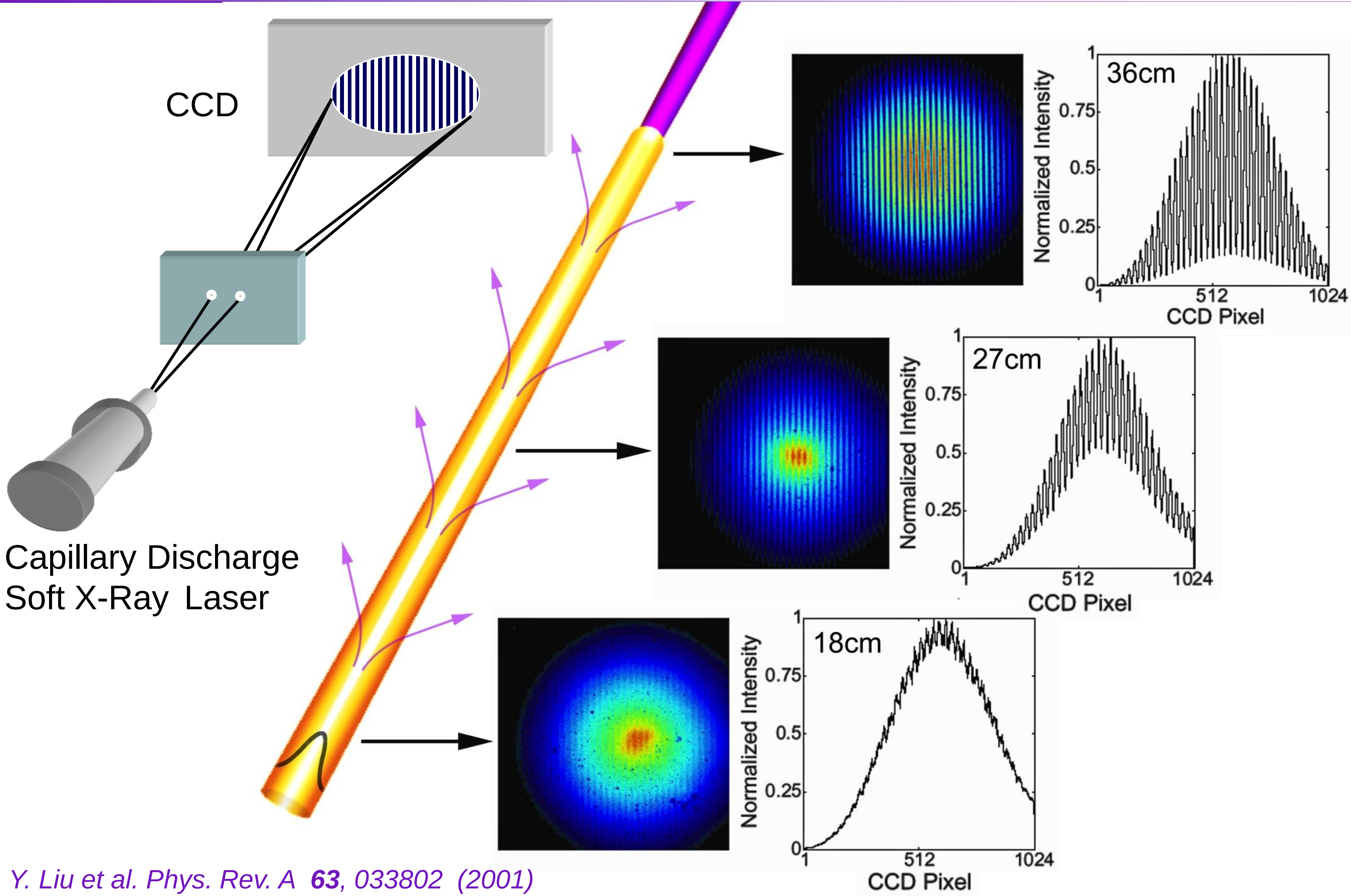
Smallest SXRL laser , λ=46.9 nm



- •10 microjoule /pulse
- • 0.15 mW average power
- •1-12 Hz repetition rate
- • Pulse duration ~1.5 ns
- • $\Delta\lambda/\lambda < 1 \times 10^{-4}$

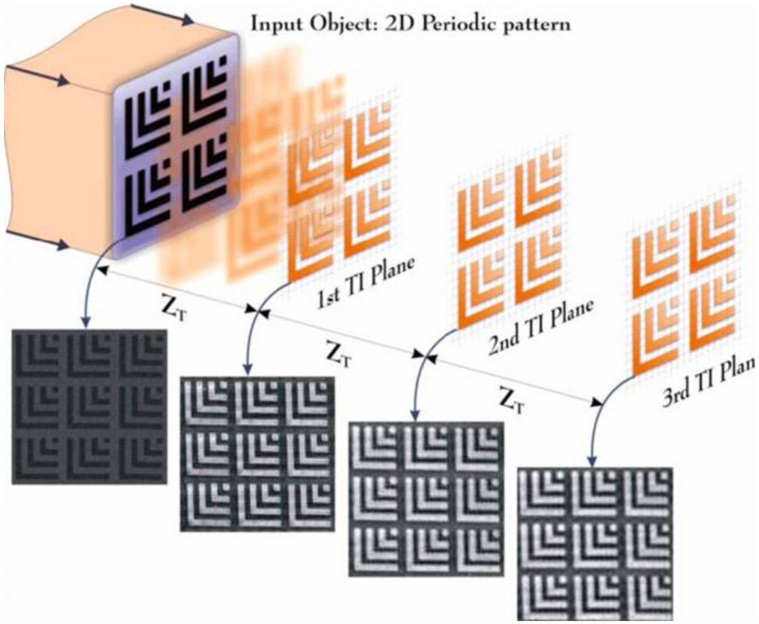
S. Heinbuch, M. Grisham, D. Martz, J.J. Rocca
Optics Express, 30,2095, (2005)

Essentially full spatial coherence is achieved increasing the capillary length

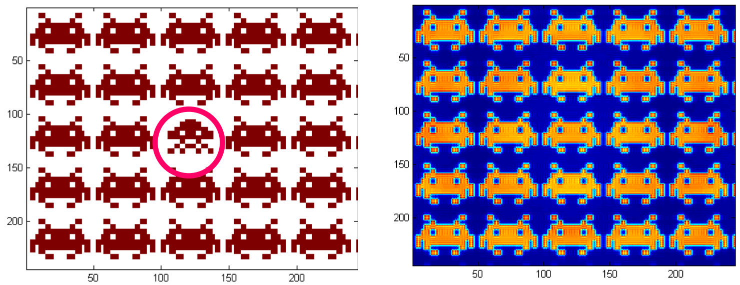


Y. Liu et al. Phys. Rev. A ***63****, 033802 (2001)*

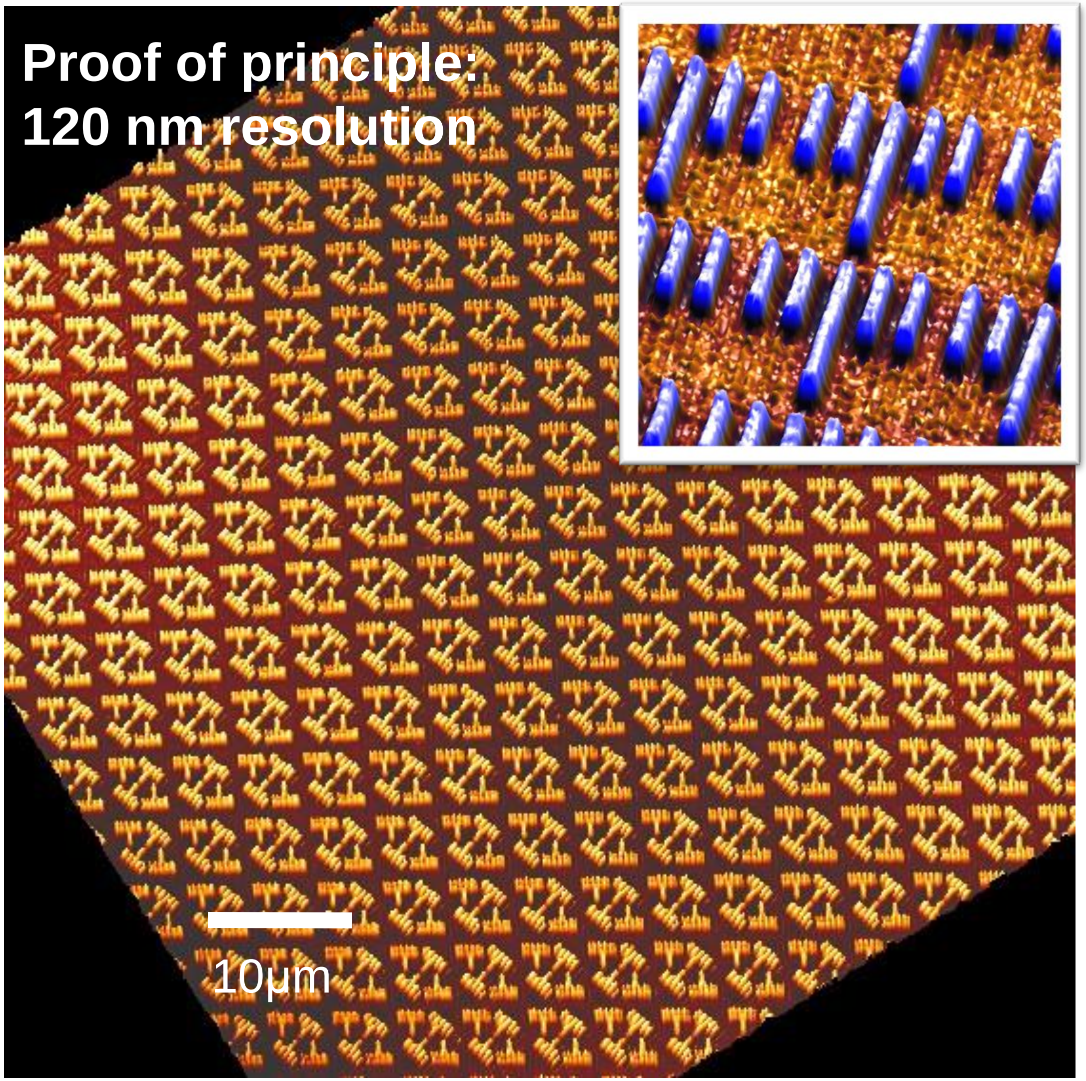
Talbot lithography: Coherent illumination of a periodic mask prints arrays of arbitrary features error-free



Error free printing

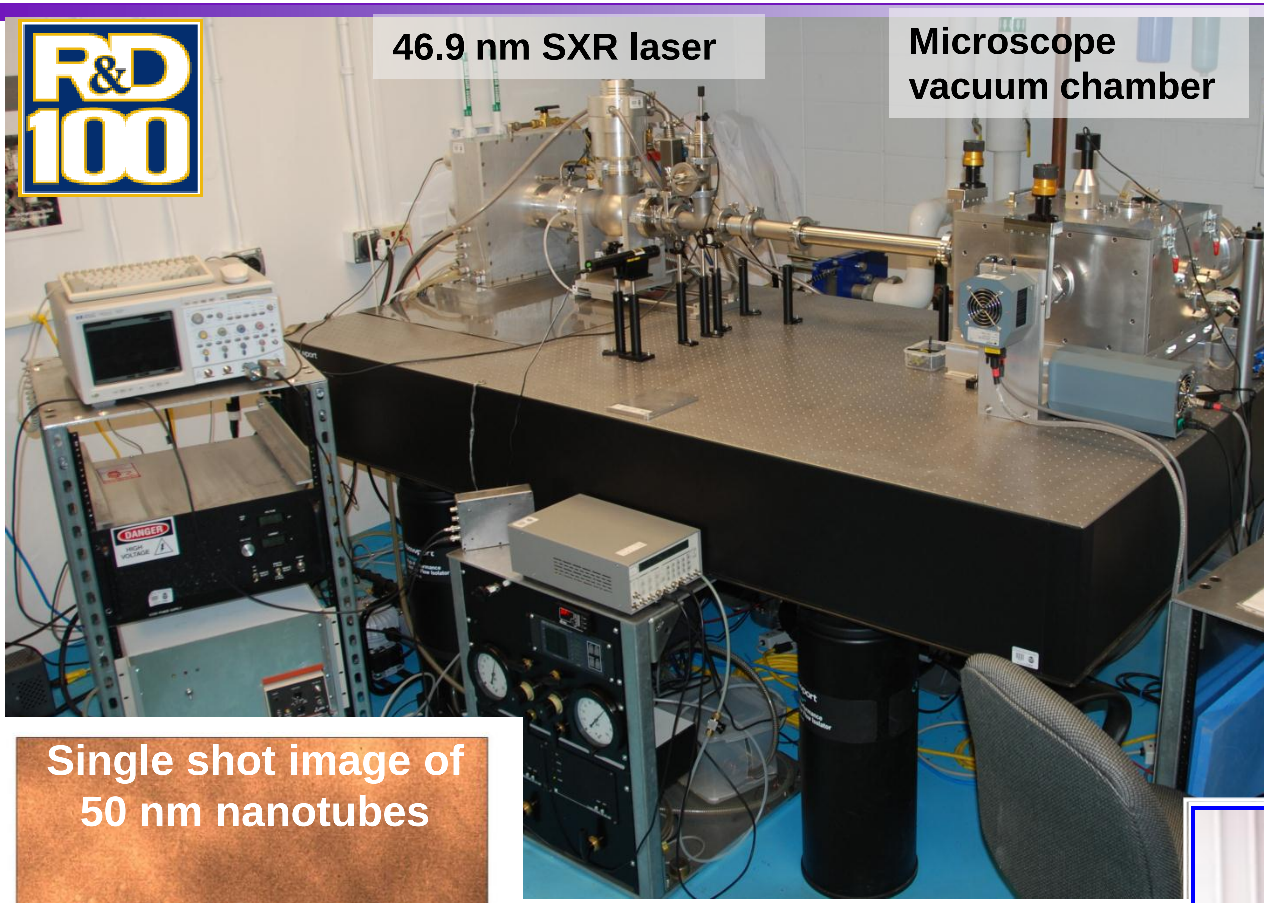


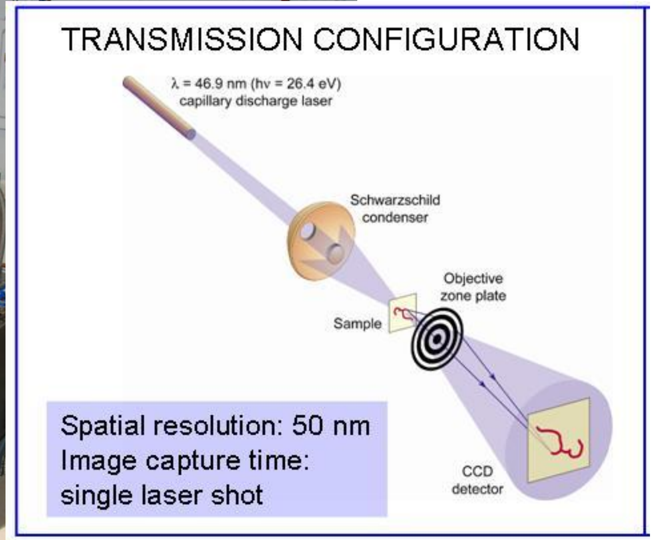
M. Marconi, F. Cerrina, et al. (2009)

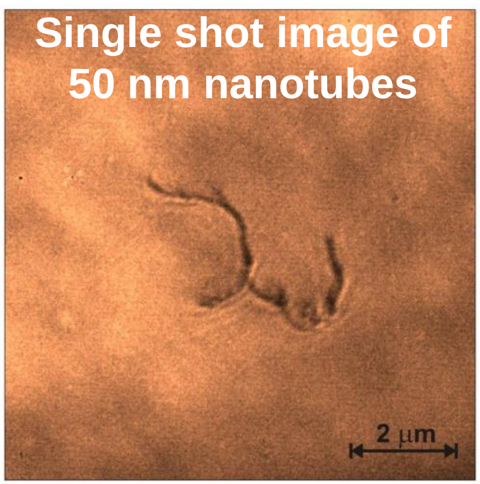


A. Isoyan et al. JVST B 37, 2931, (2009), L. Urbanski et al. Optics Letters (2012)

Compact λ= 46.9 nm full field microscope

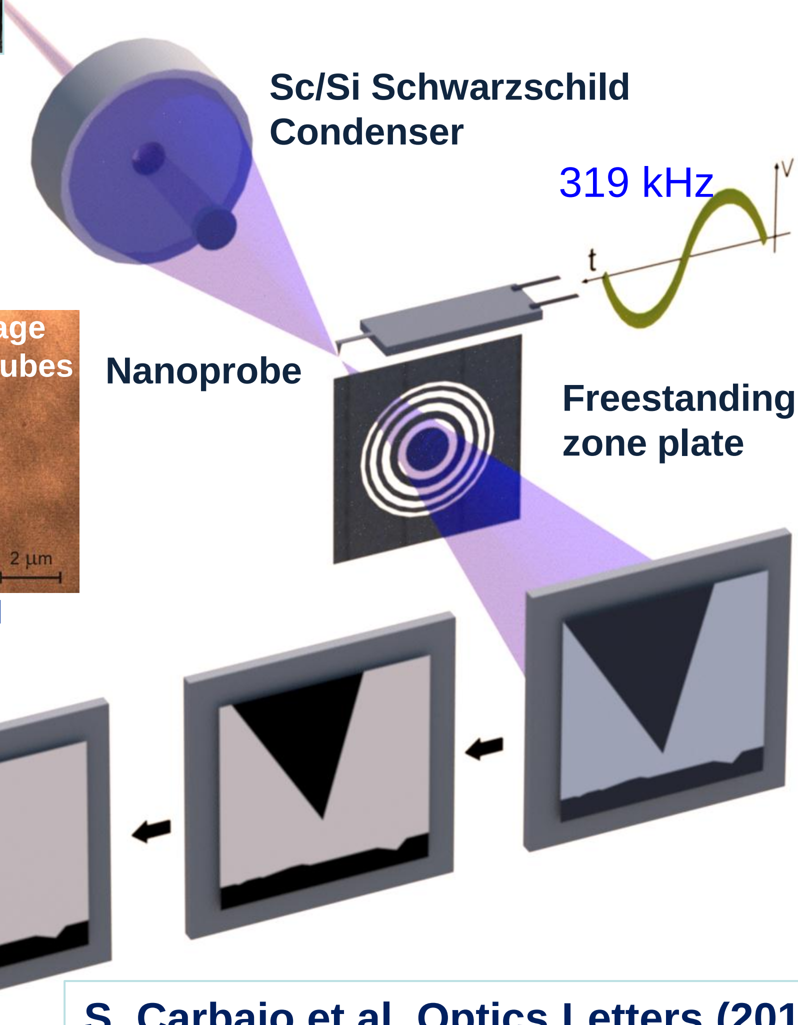


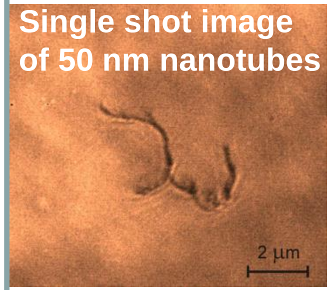




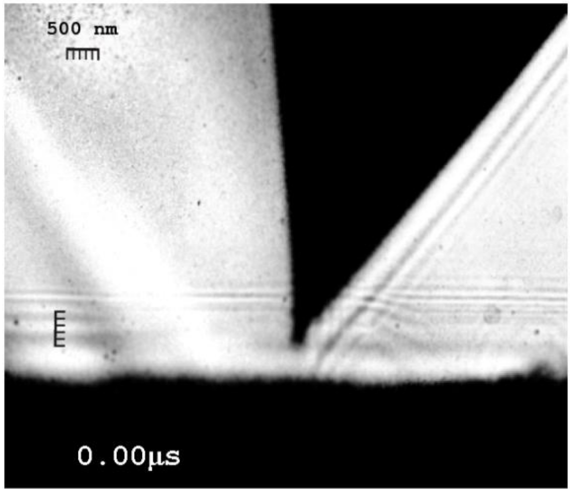
C. Brewer, et al, Opt. Lett. ***33****, 518 (2008)*

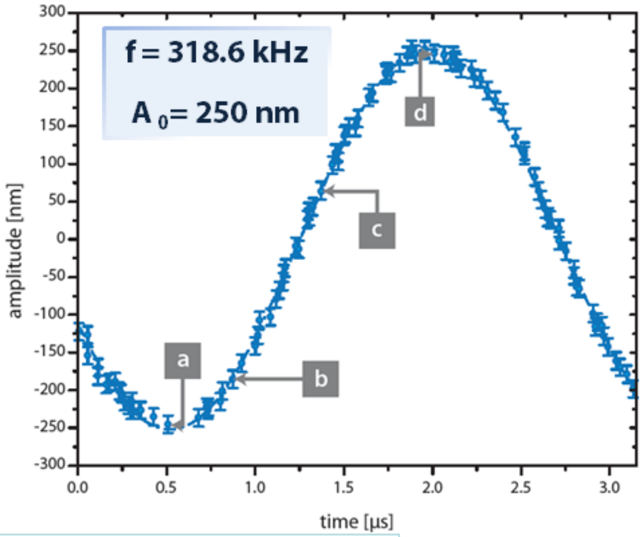
Movies of Nano-scale Dynamics on a Table-top





B. Brewer et al Optics Lett. 33,518,(2008)

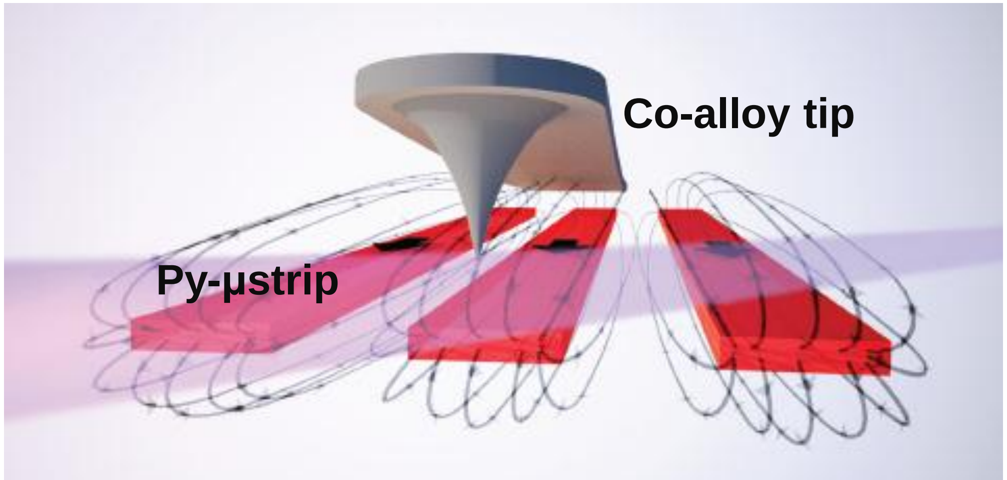


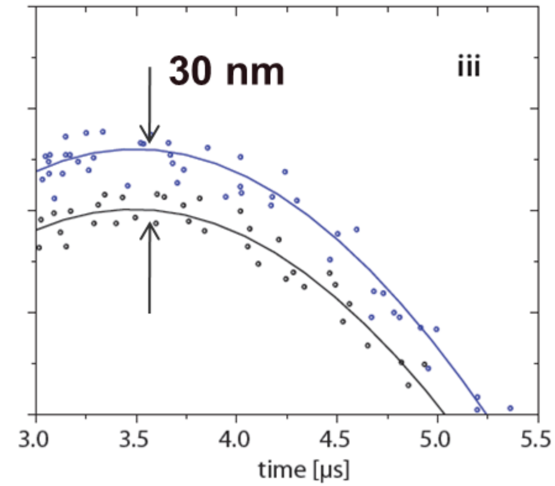


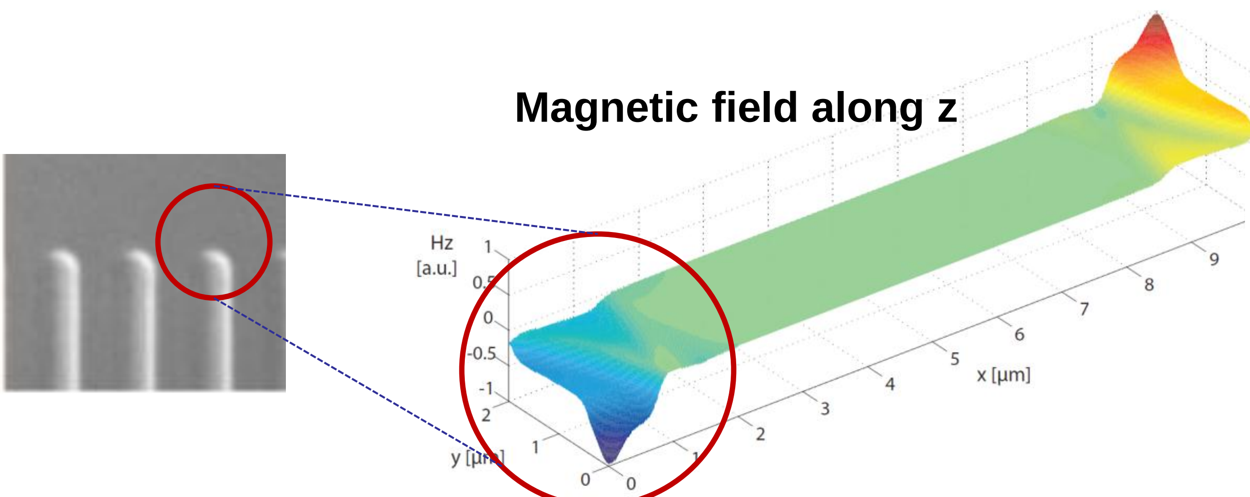
S. Carbajo et al. Optics Letters (2012)

Visualizing Nano-scale Dynamic Interactions

Magnetic force microscope tip interaction with stray magnetic field



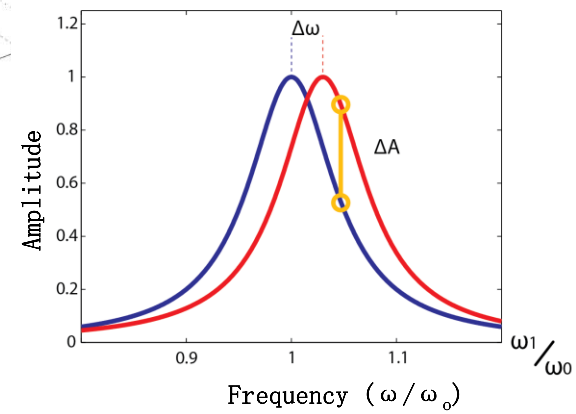




Effective Spring Constant

***k*tip + *k*force**

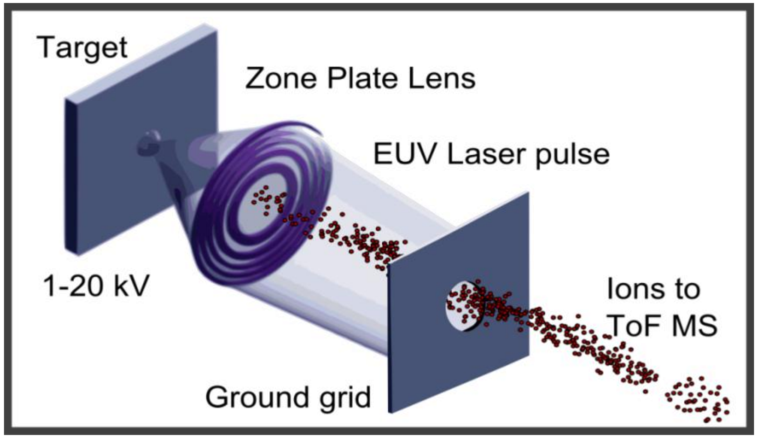
$$\omega_{res}^2 = k/m = 1/m\,(k - \partial F/\partial z)$$

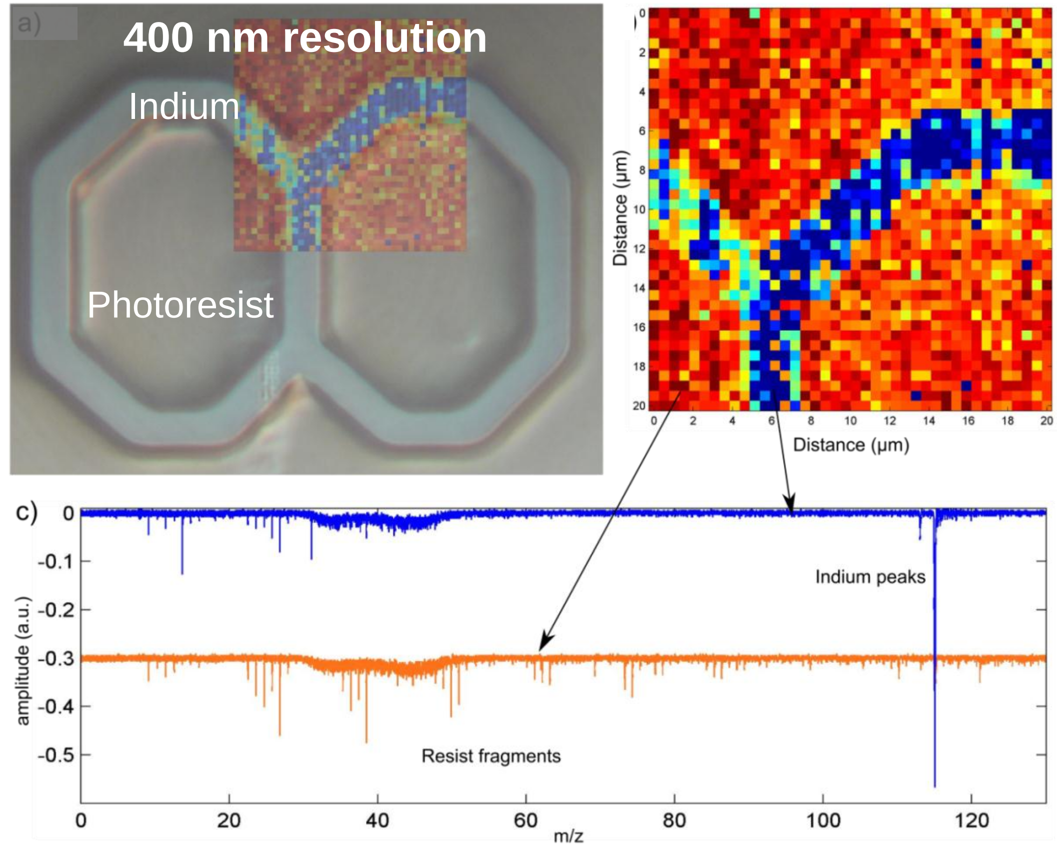


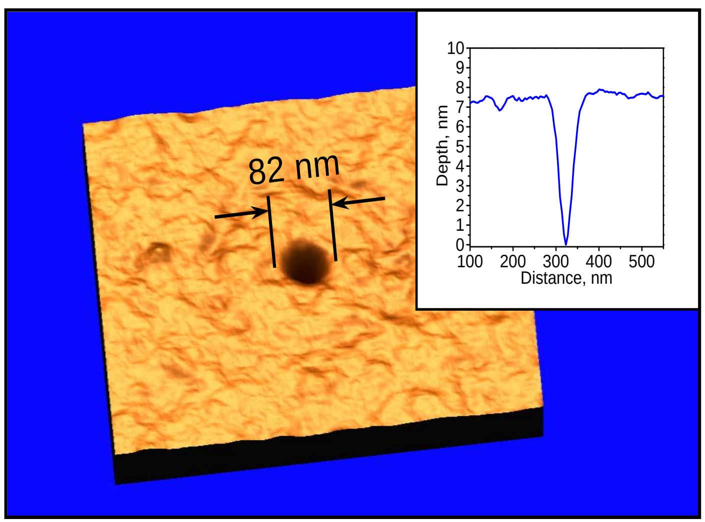
S. Carbajo et al. Optics Letters (2012)

SXRL Ablation Mass Spectrometry Imaging Nanoprobe

3-D maps of materials composition with nanometer resolution

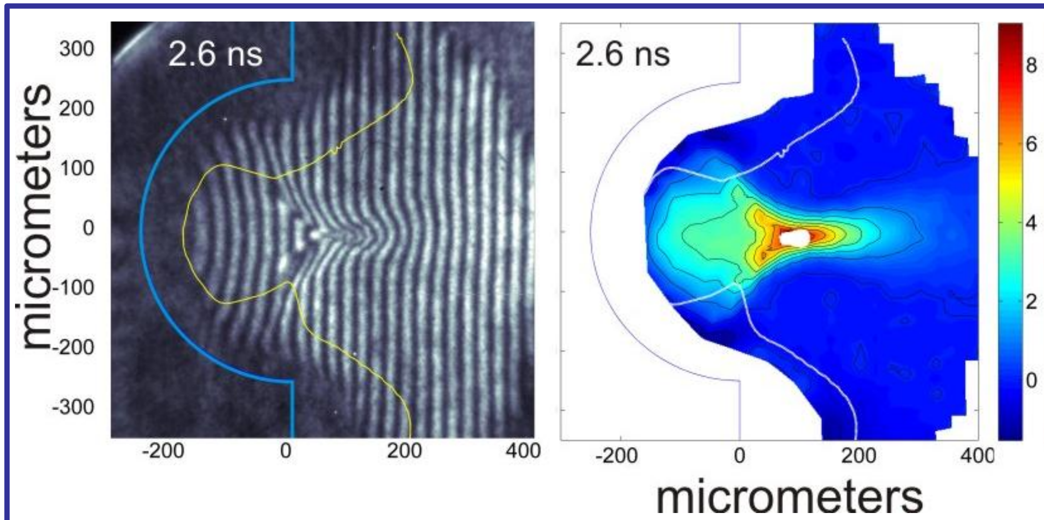






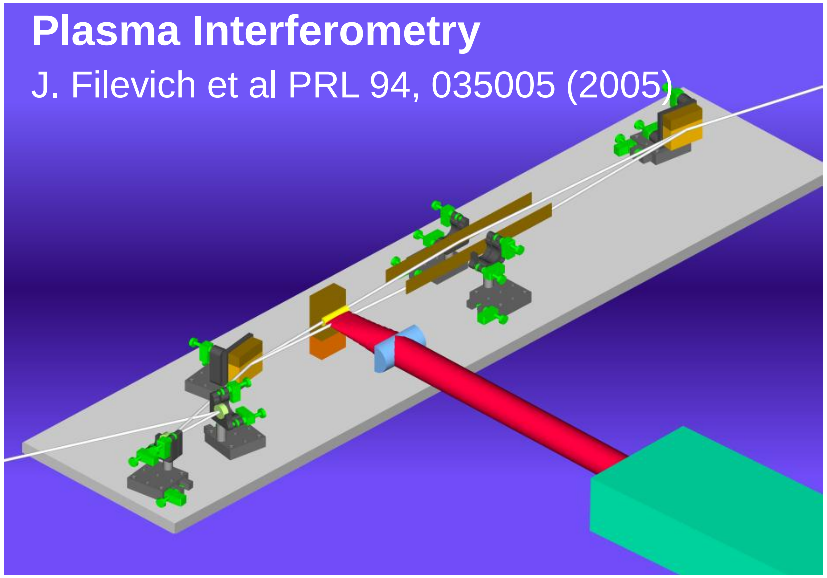
C.S. Menoni et al. **Int. Conference, on X-Ray Lasers, Paris, June (2012)**

Applications in dense plasma diagnostics and photochemistry

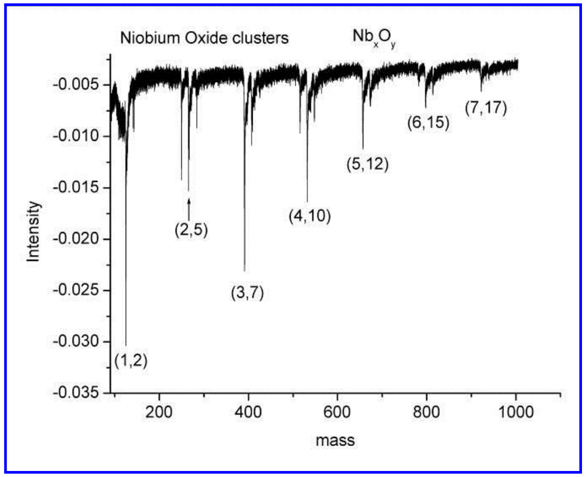


Plasma Interferometry

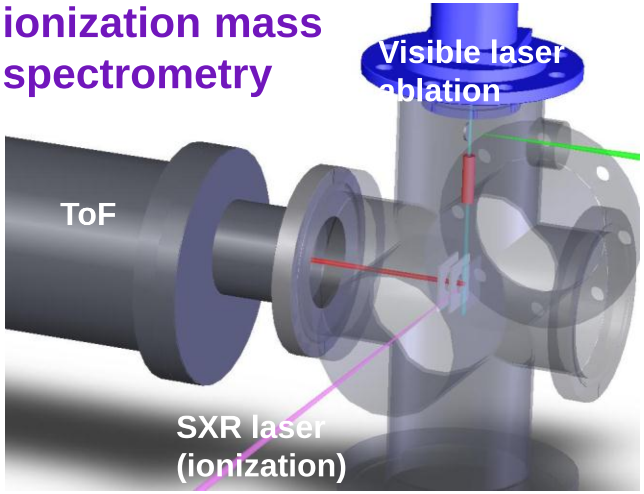
J. Filevich et al PRL 94, 035005 (2005)



*M. Purvis et al. Phys. Rev.E, **76**, (2007); **124**, (2010)*



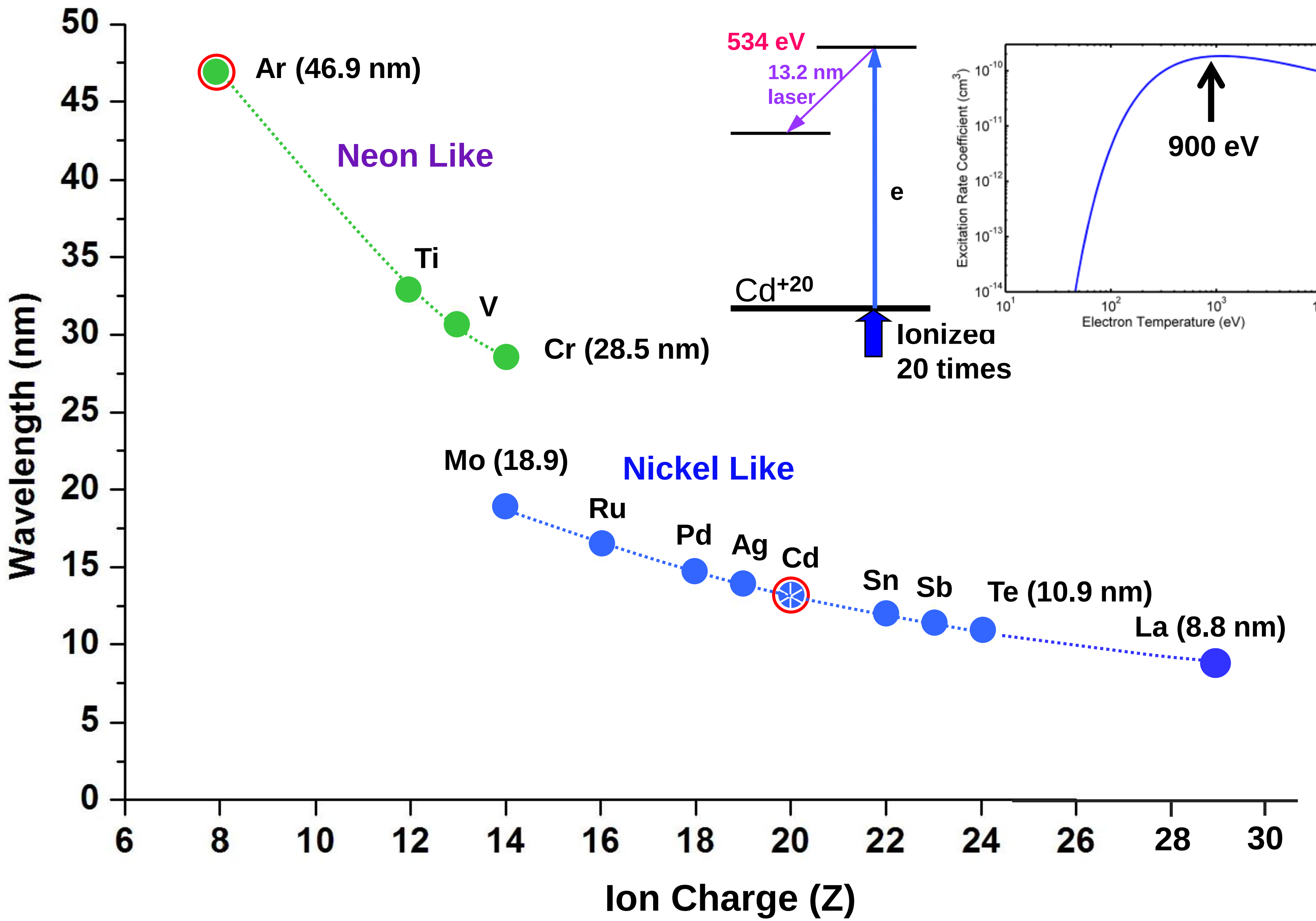
Single photon ionization mass spectrometry



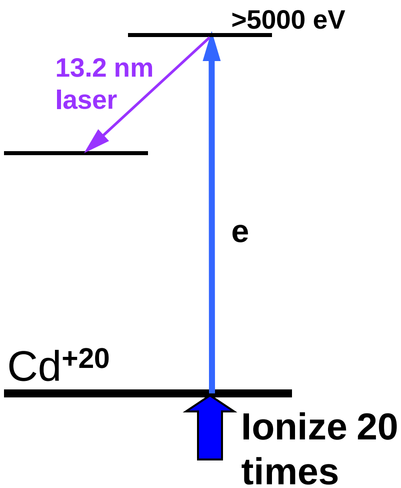
*F. Dong et al. J.Chem.Phys **124,** (2006)*

*F. Dong et al. J.Am.Chem Soc. **131**, (2009)*

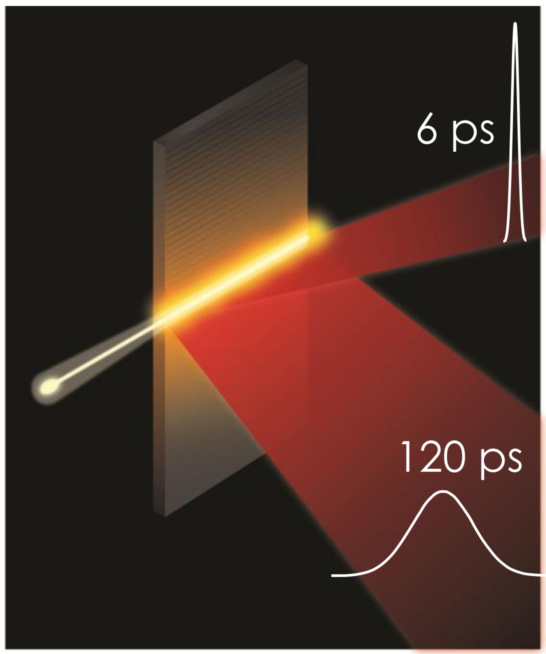
Scaling to shorter wavelengths requires hotter-denser plasmas



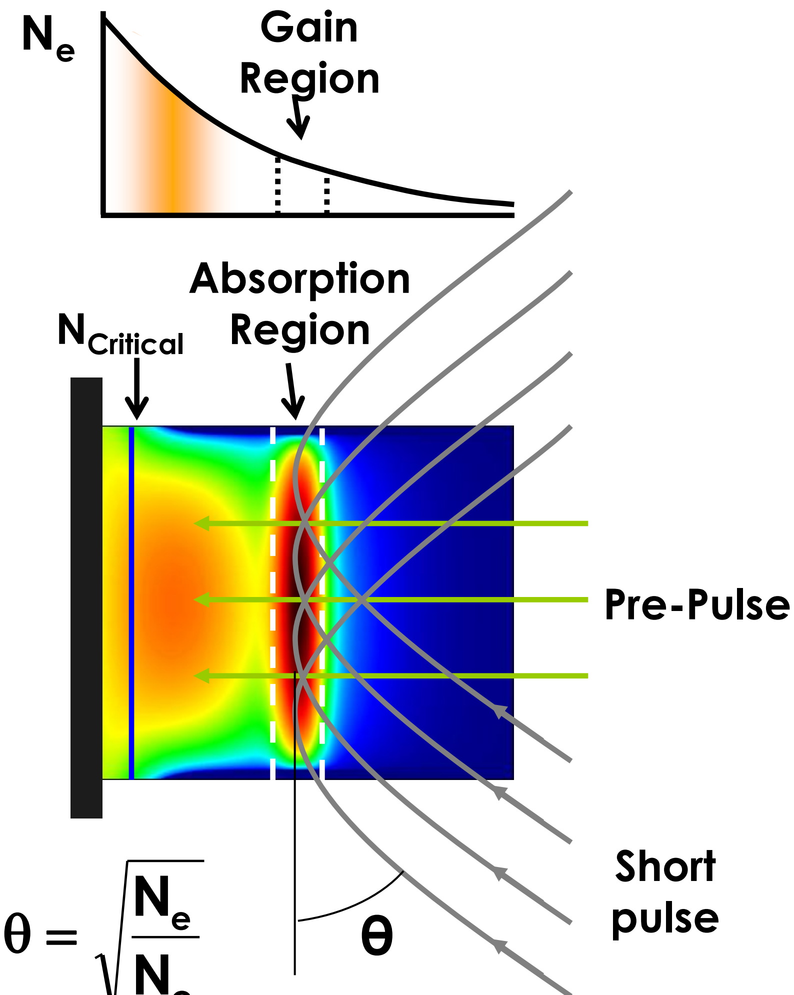
Soft X-ray lasers excited by rapid heating of plasmas with short laser pulses



Laser Pumping Geometry



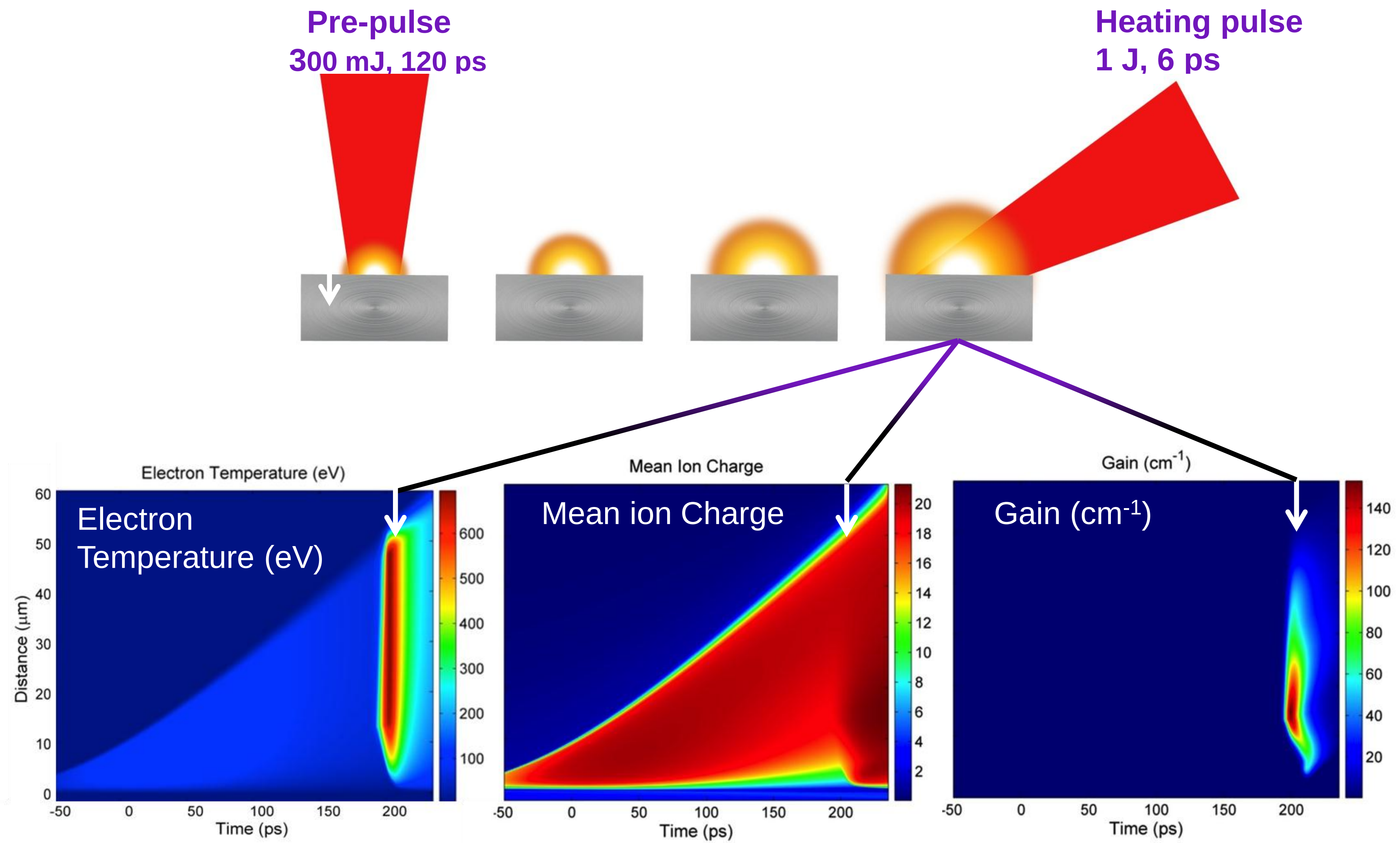
Grazing incidence allows for efficient heating of plasma region with optimum electron density



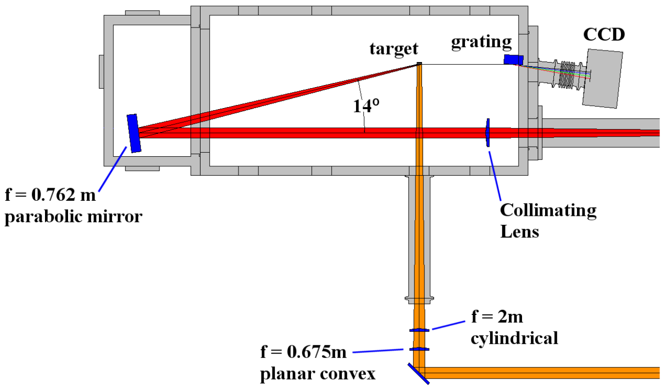
$$\theta = \sqrt{\frac{N_e}{N_c}}$$

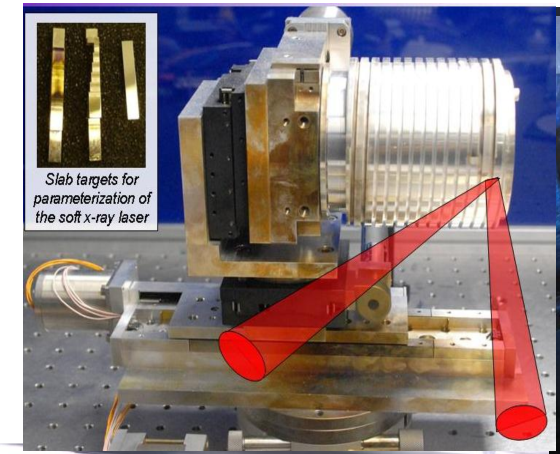
R. Keenan et al, Phys. Rev. Lett. 94, 103901 (2005) ; B.M. Luther et al, Opt. Lett. 30, 165 (2005); Transient excitation: P. Nickels, V. Shlyaptsev et al. Phys. Rev.Lett. 78,2 748, (1997)

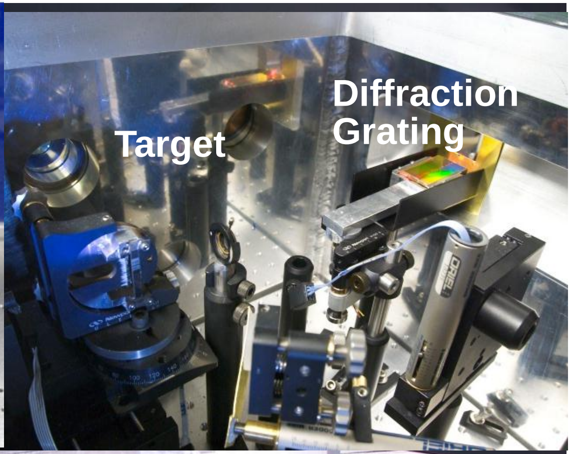
Simulation showed gain-saturated amplification at 13.2 nm in Ni-like Cd can be achieved with ~ 1 J pump

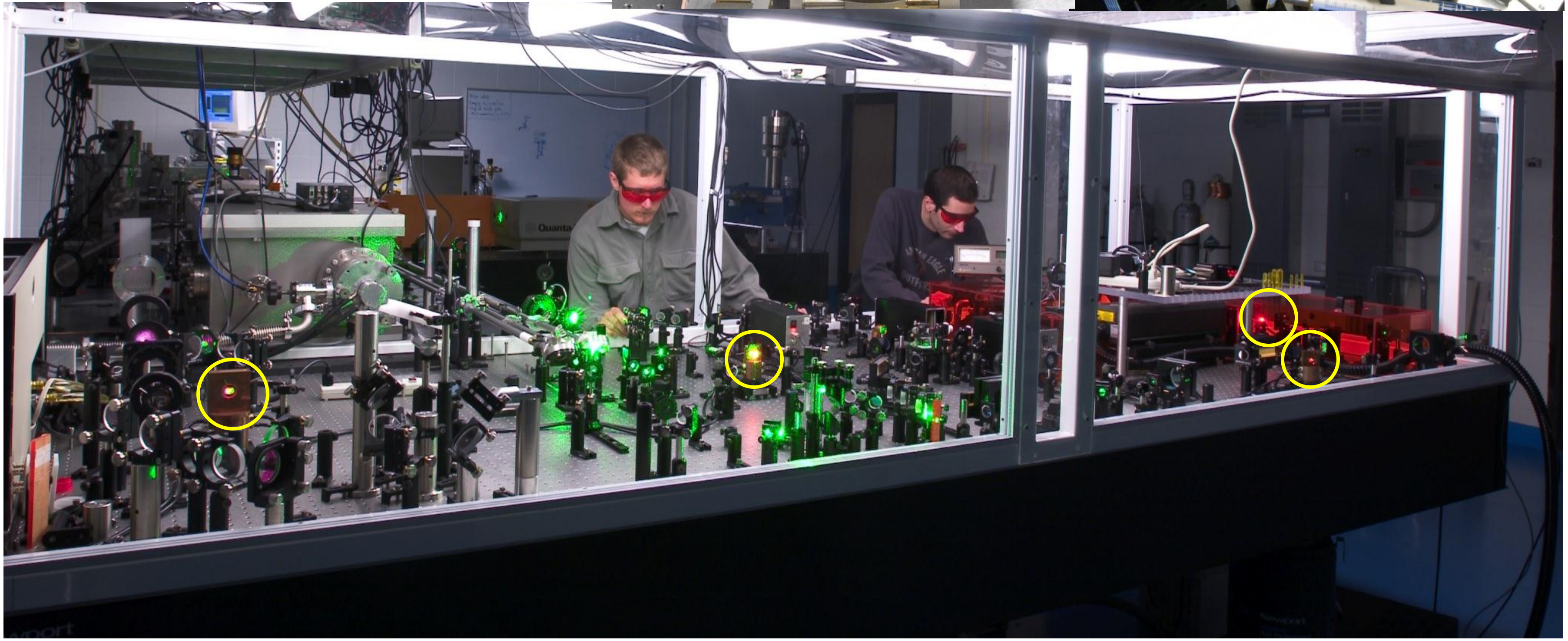


Lasers pumped by a 5-10 Hz ~ 1 J Short Pulse Table-top Ti: Sapphire System

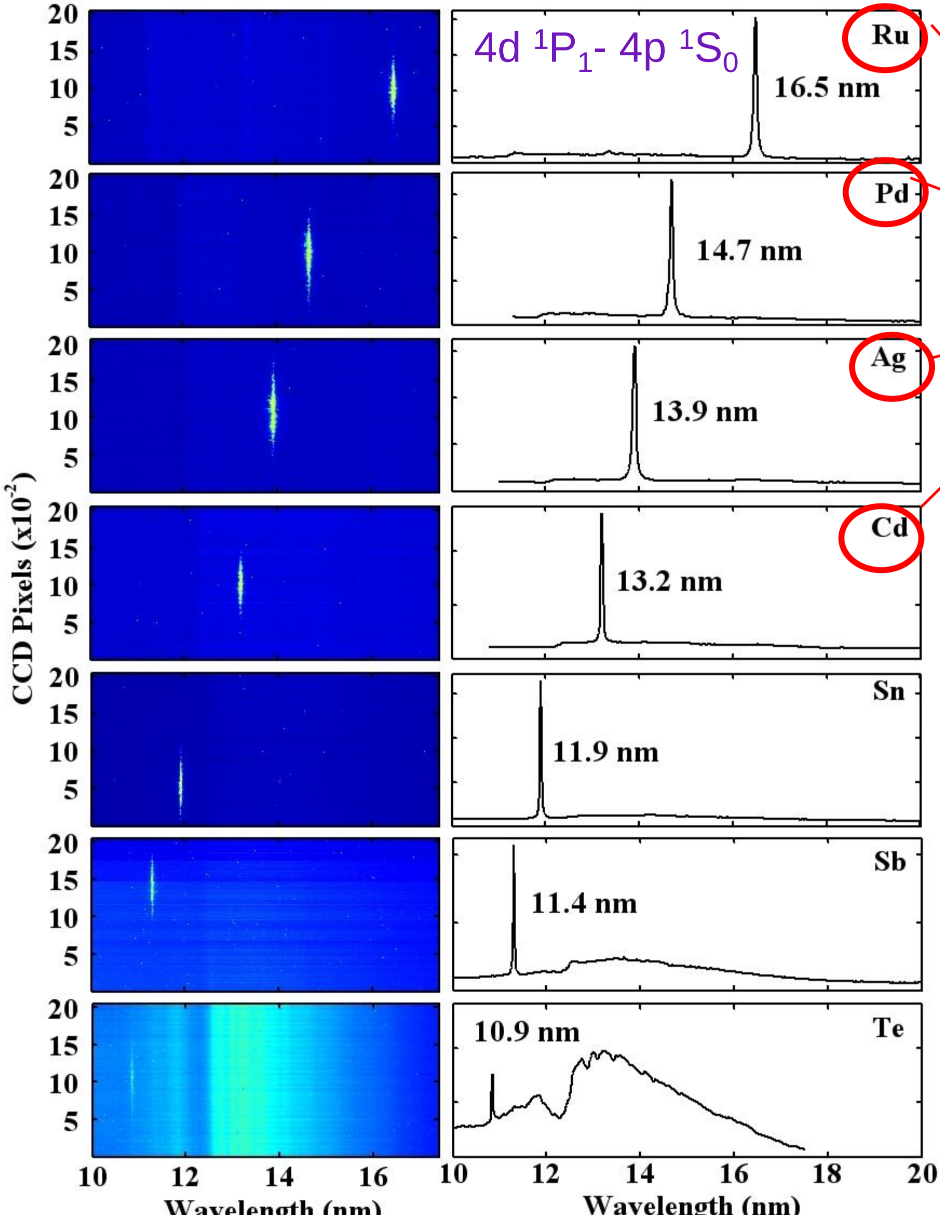




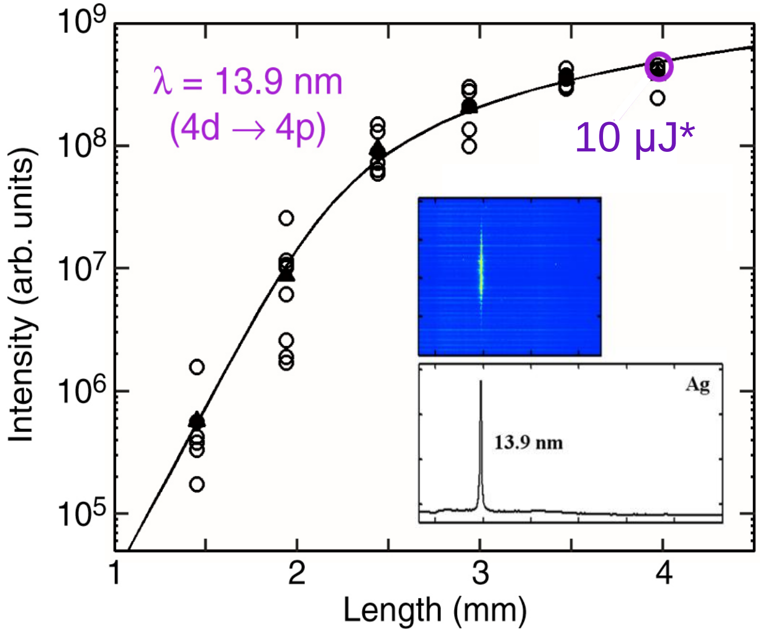




High repetition rate table-top SXRL in transitions of Ni-like ions down to 10.9 nm



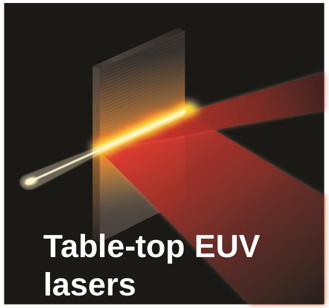
Gain saturated operation demonstrated

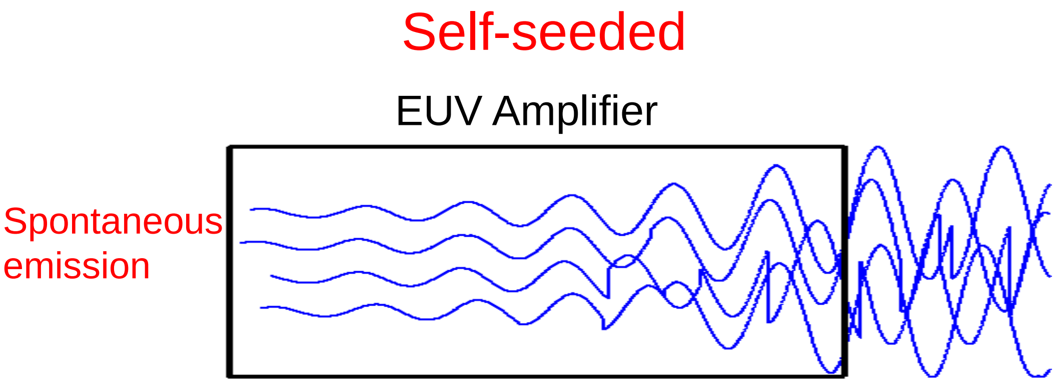


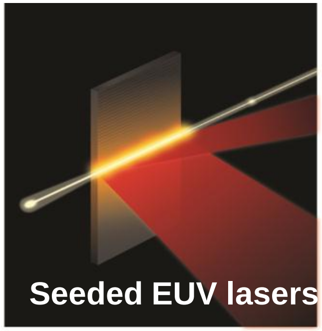
*Y. Wang et al, Phys. Rev. A **72**, 053807 (2005)*

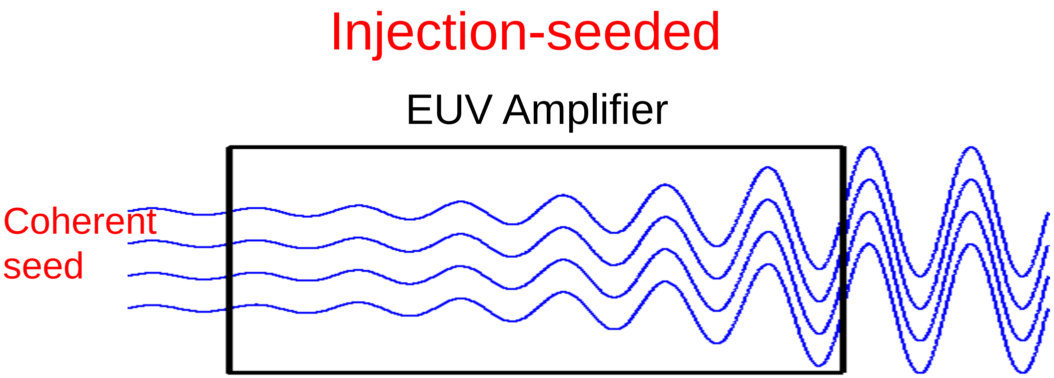
D. Martz et al. Optics Lett. **35, 1632 (2010)*

SXR lasers self-seeded by spontaneous emission noise have poor temporal coherence



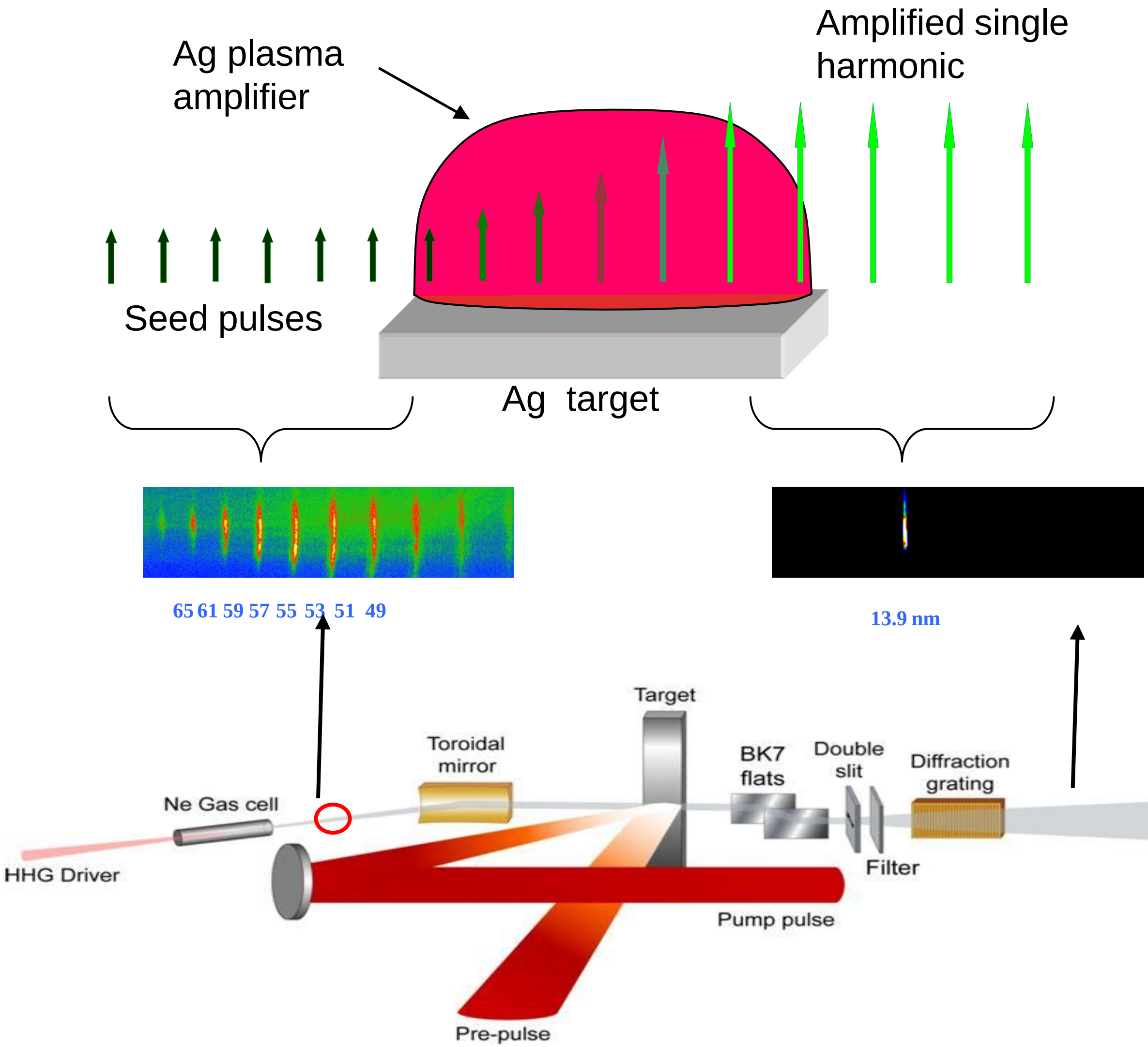




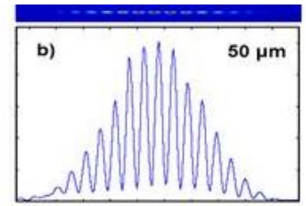


Seed pulses can be greatly amplified preserving or even improving their properties

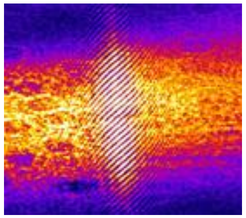
Injection-seeding SXR Lasers have full phase-coherence and shorter pulsewidth



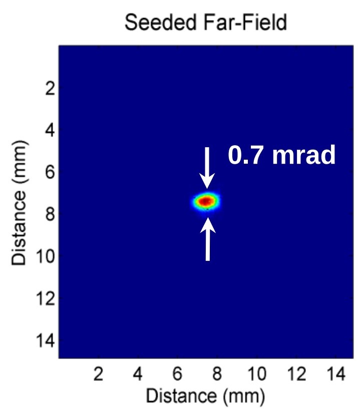
Full spatial coherence



Full temporal coherence

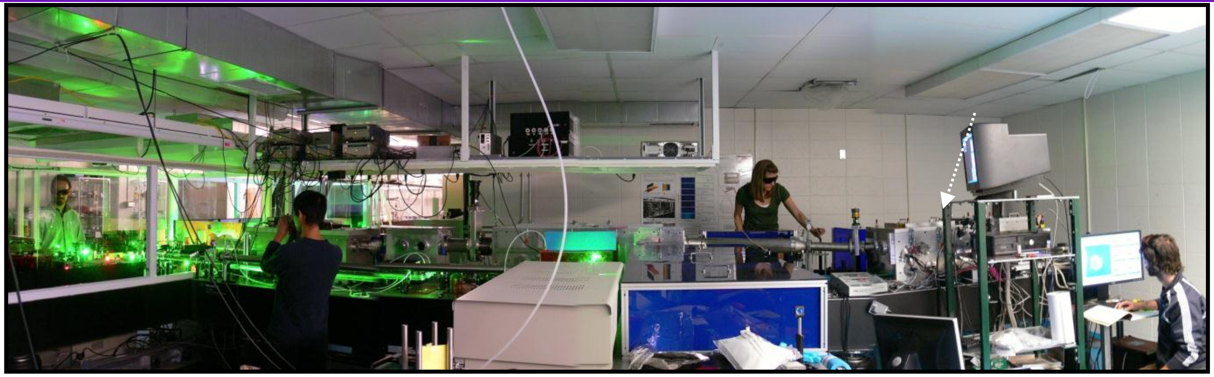


Shorter pulsewidth
(1.13±0.47)ps

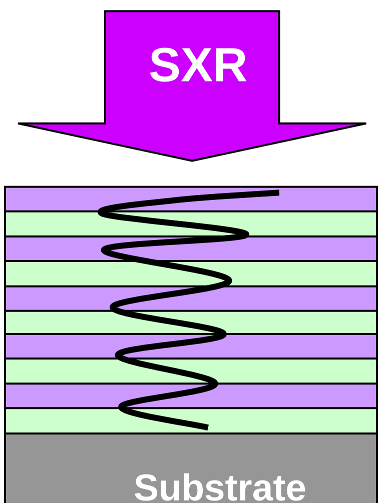


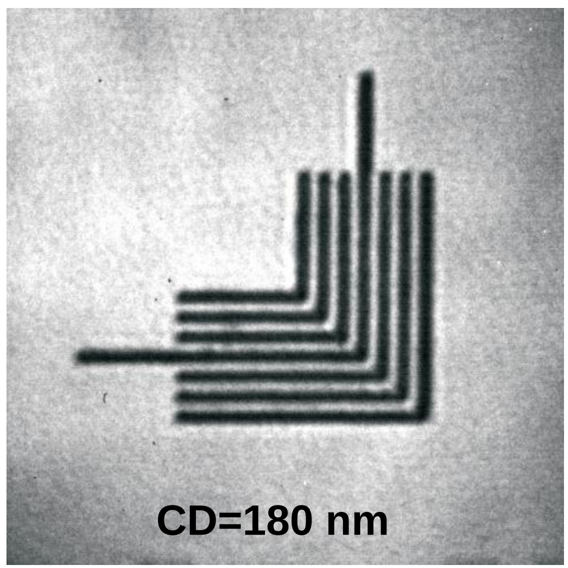
T. Ditmire et al. Phys. Rev. A. ***51****, R 4337, (1995); P. Zeitoun et al. Nature,* ***431****, 427, (2004) ;*
Y. Wang et al. Phys. Rev. Lett, ***97****, 123901 (2006) Y. Wang et al. Nature Photonics,* ***2****, 94, (2008)*

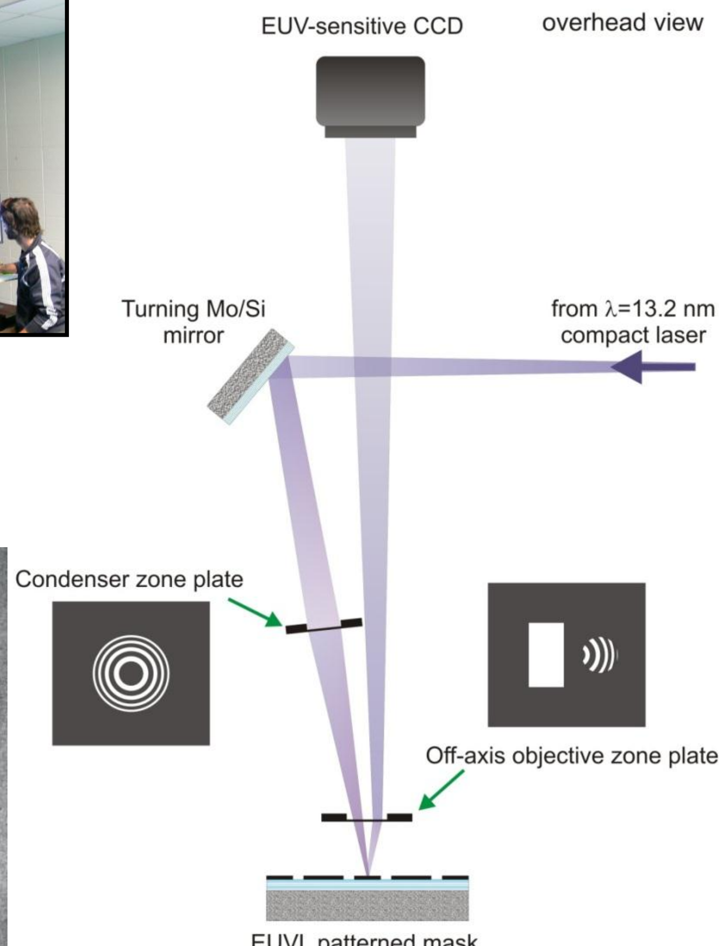
13.2 nm laser-based microscope for defect inspection in EUV lithography masks



λ= 13.2 nm resonant with Mo/Si coatings in extreme ultraviolet lithography masks



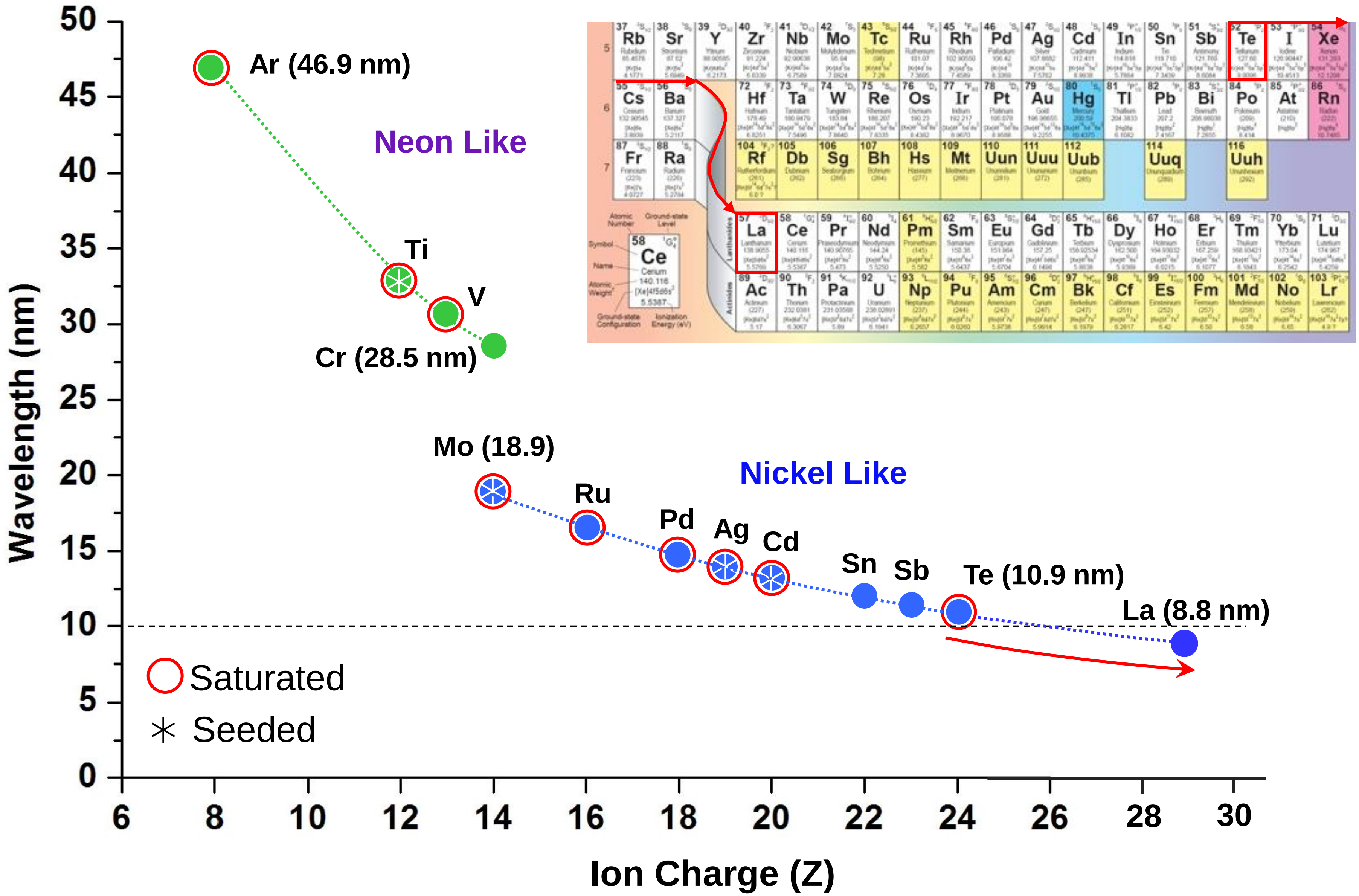




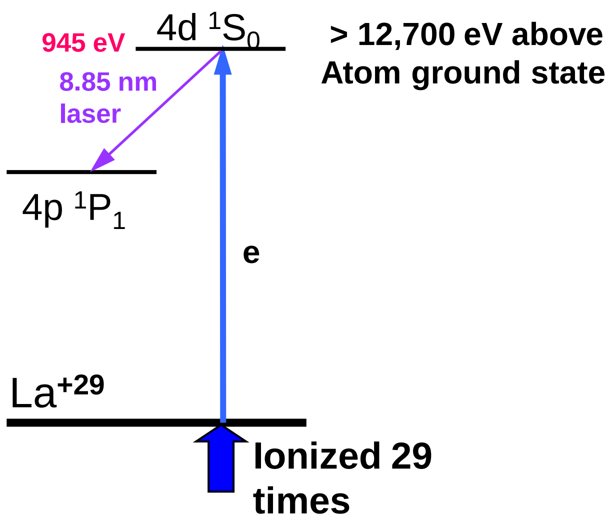
EUV Optics from CXRO, Berkeley

F. Brizuela et al., *Optics Express* ***18****, 14467, (2010)*

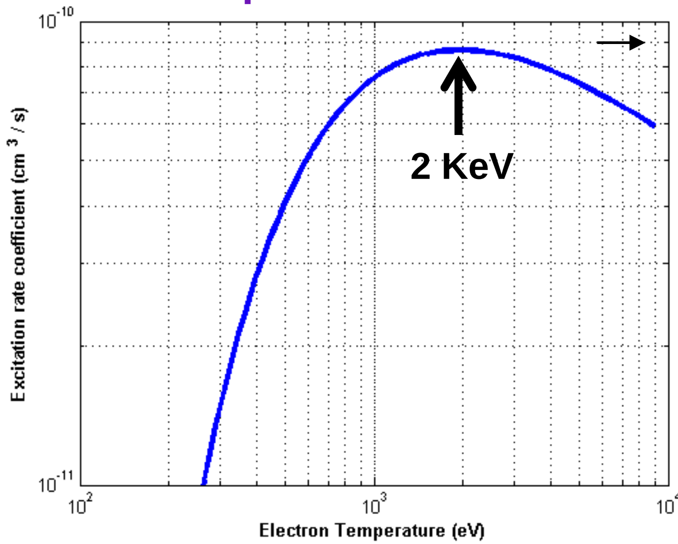
Extension of gain-saturated table-top SXRL to sub-10 nm wavelengths using lanthanide ions



Electron impact excitation of 8.8 nm La laser requires plasma with high electron temperature

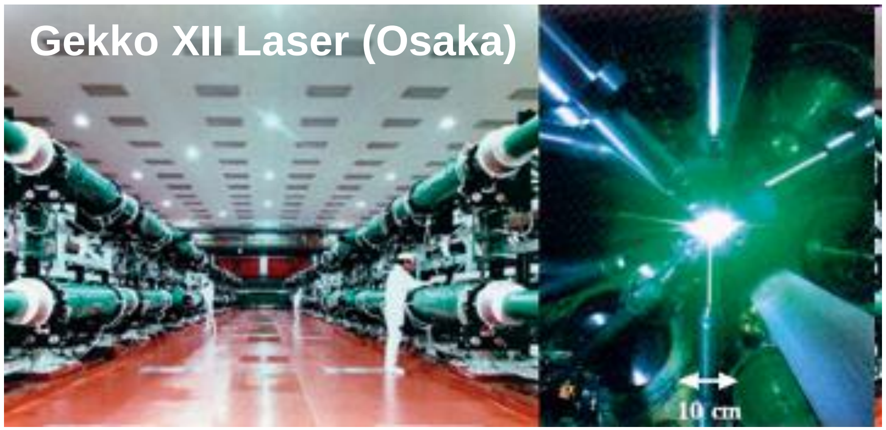


Electron impact excitation rate 4d $^1S_0$

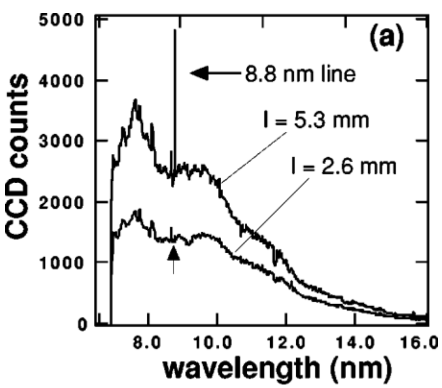


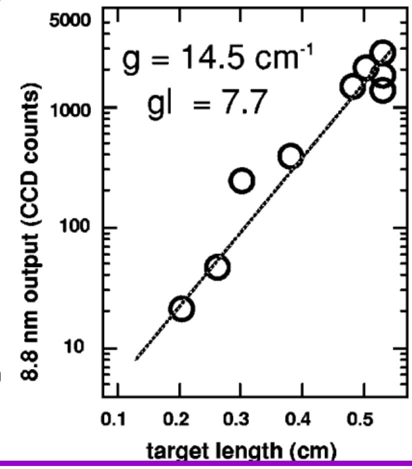
Previous work achieved unsaturated lasing at 8.8 nm in Ni-like La

*•Daido et al. using **520 J** of laser pump energy (Optics Lett. 21, 958,1996)*

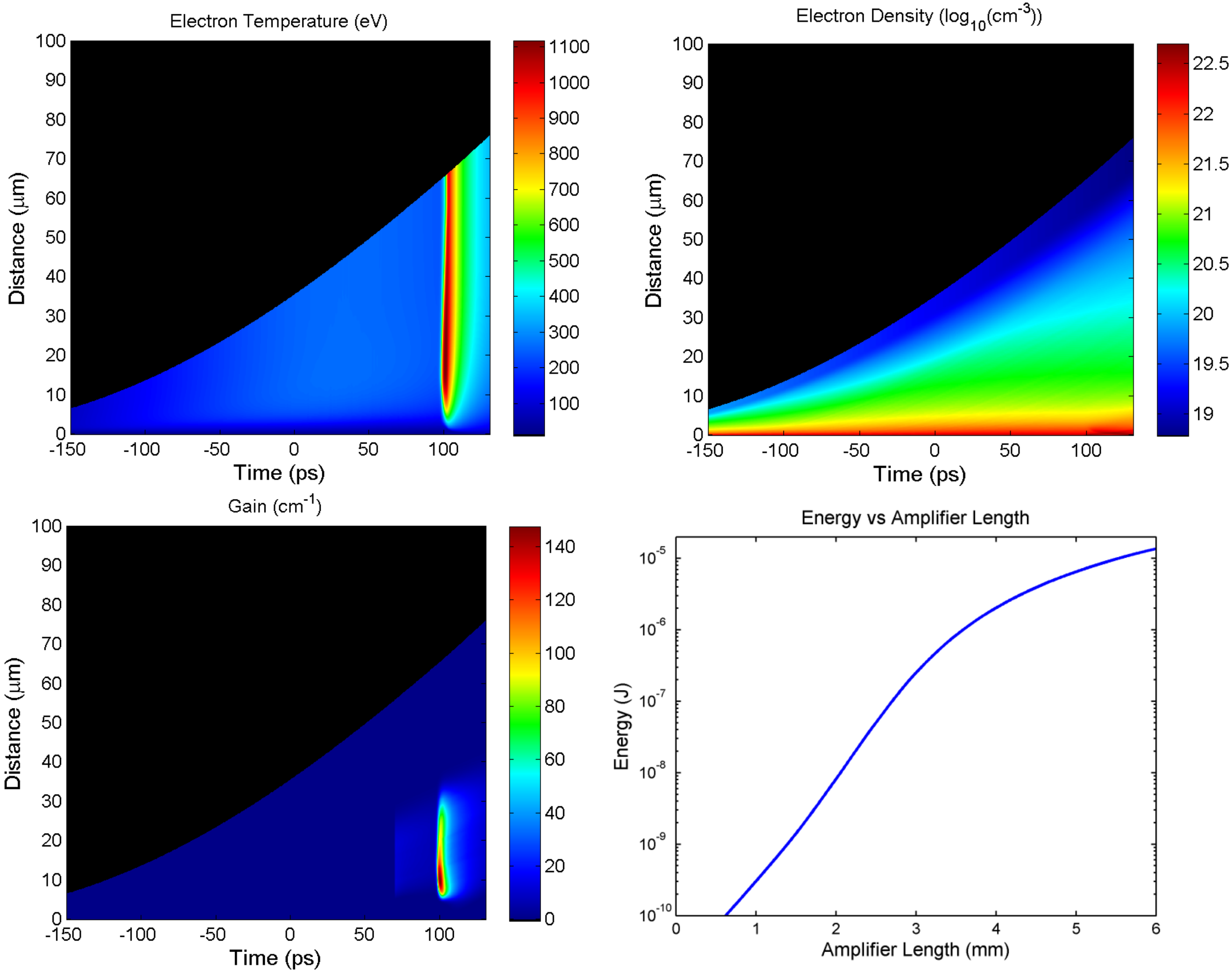


*Kawachi et al. using **18 J** picosecond pulses (Phys. Rev. A, 69, 2004)*





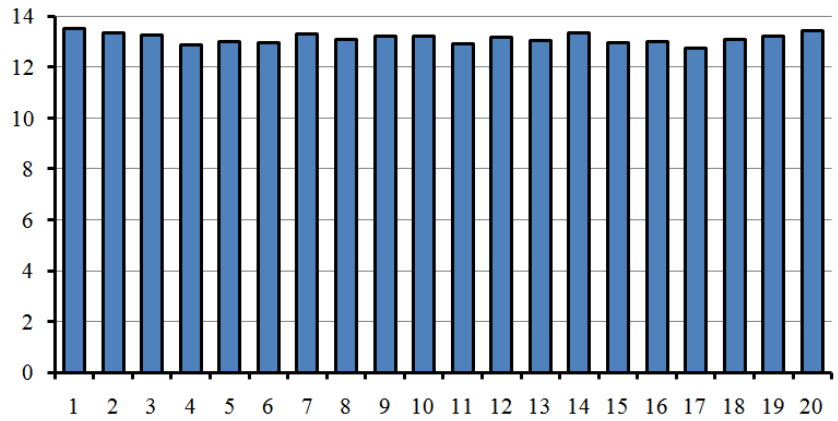
Simulation for 8.8 nm table-top Laser in Ni-like La predicts < 7 J pump energy needed for gain saturation

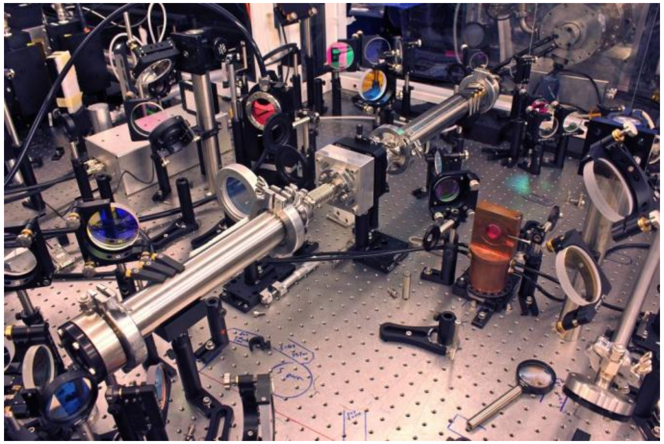


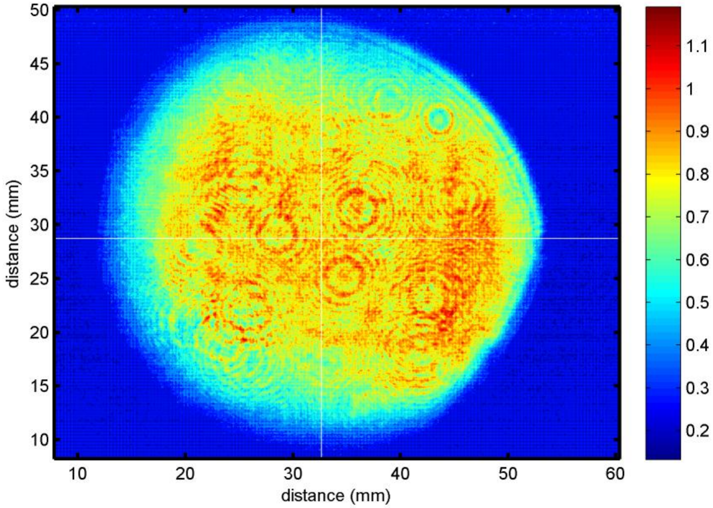
Simulation by Mark Berrill

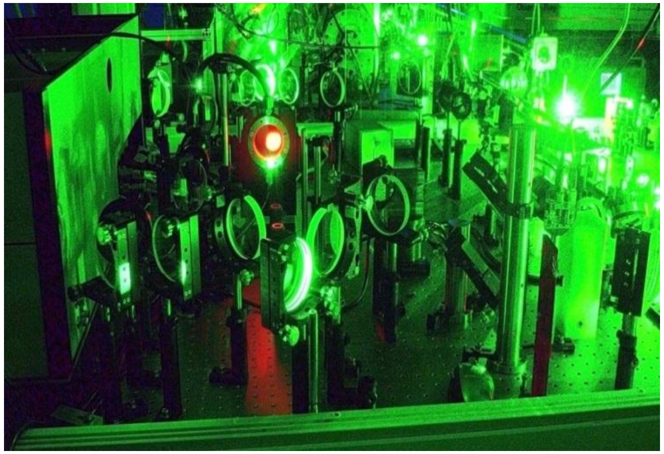
Titanium-Sapphire pump laser

Average Energy Pre-compression= 13 J
Std div. = 1.5 %

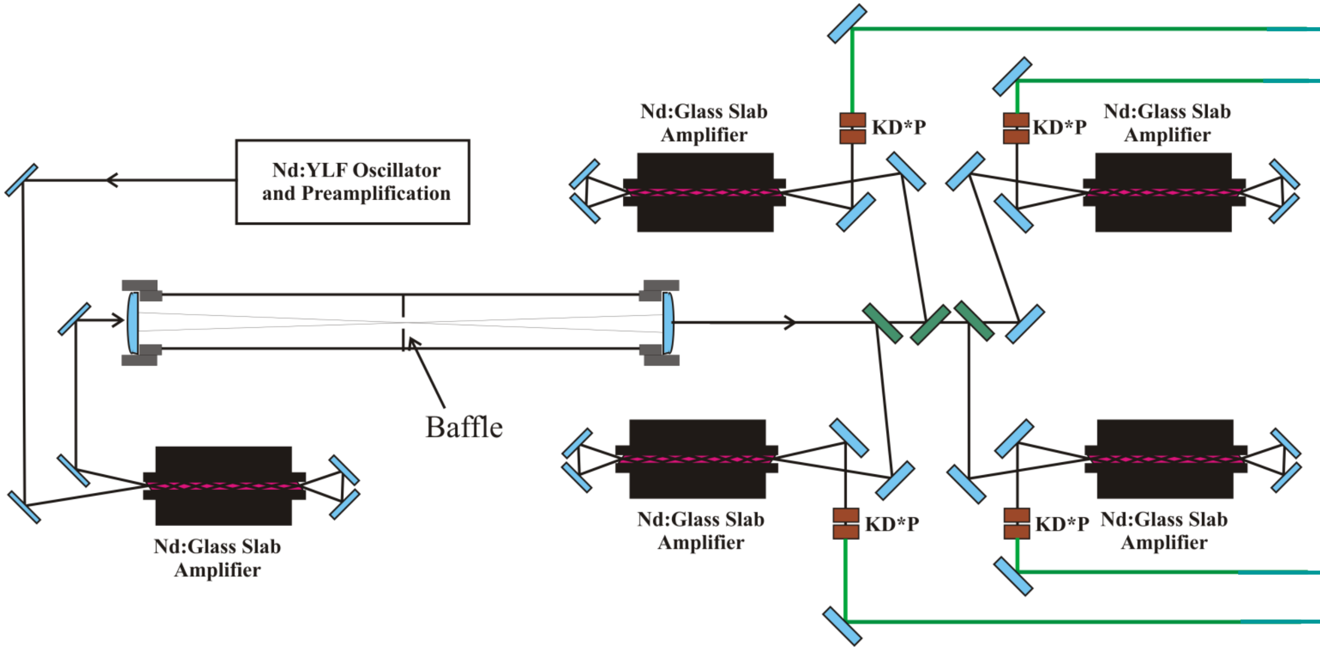


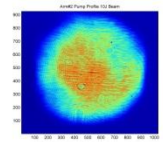


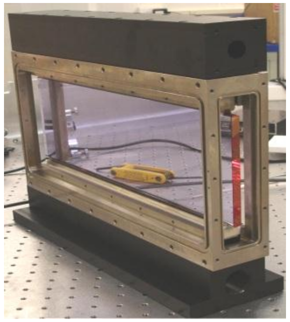


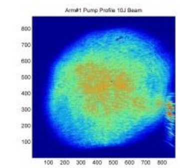


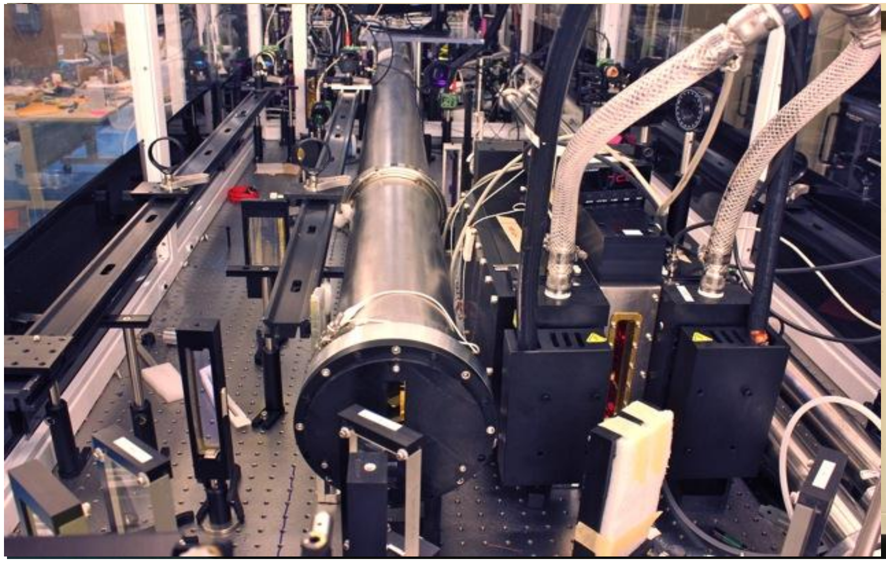
High energy pump laser for Ti:Sapphire: 35 J at 527 nm

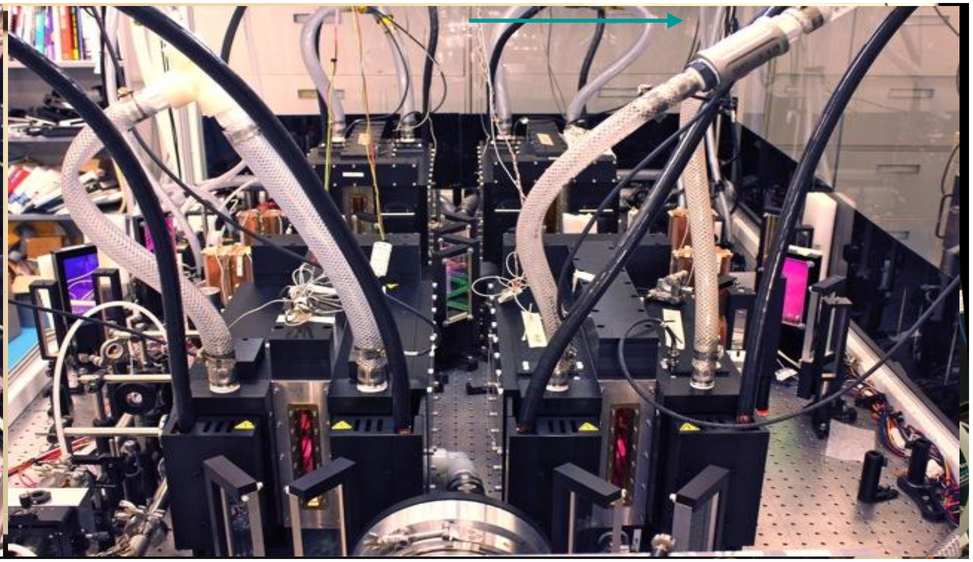




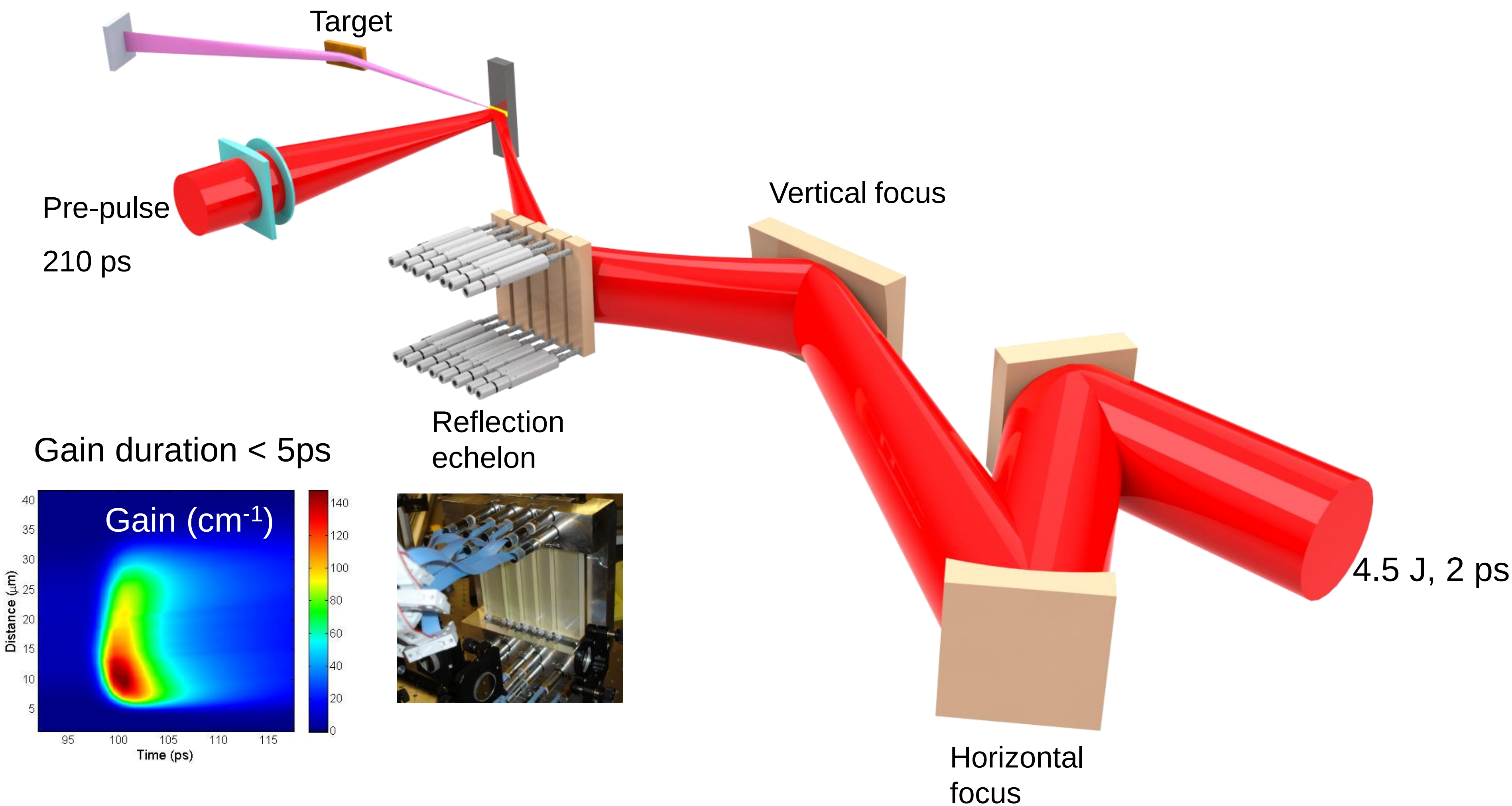






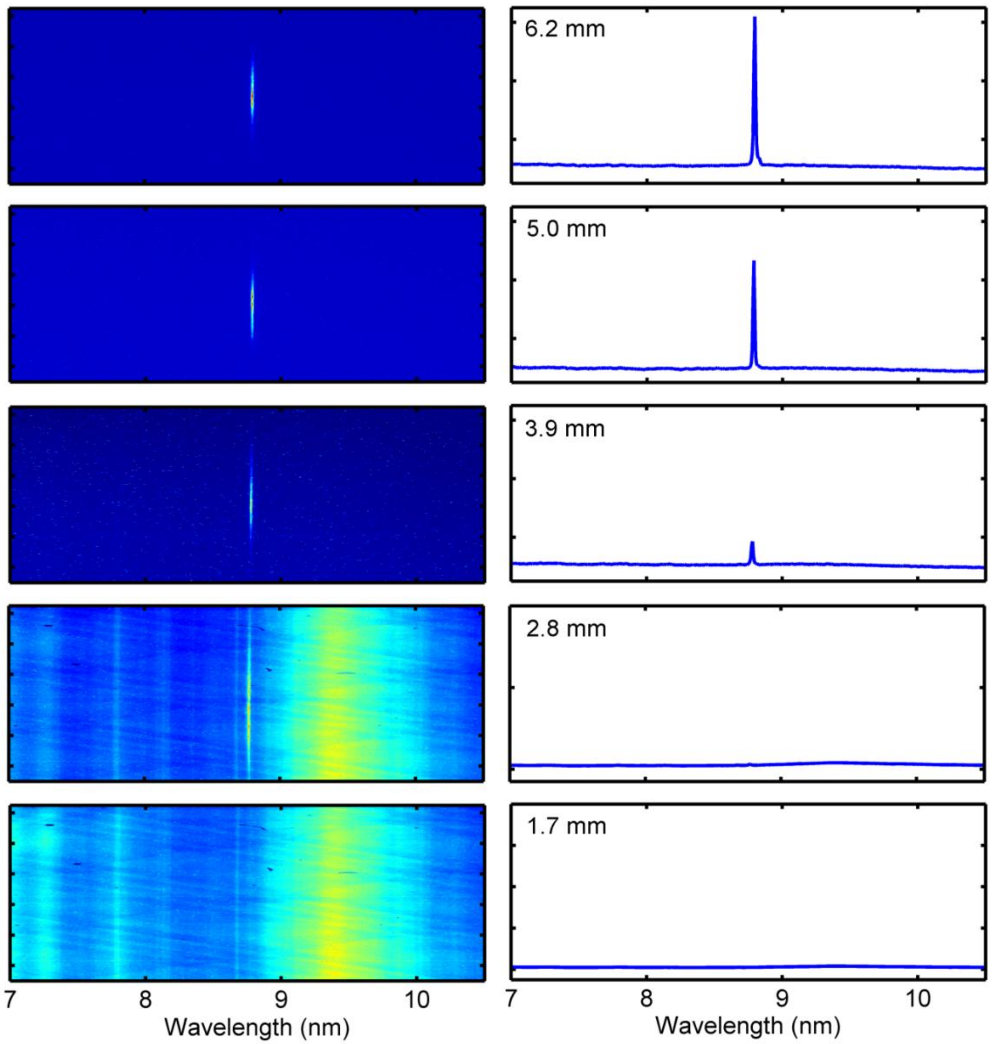


Gain-saturated sub-10 nm table-top lasers



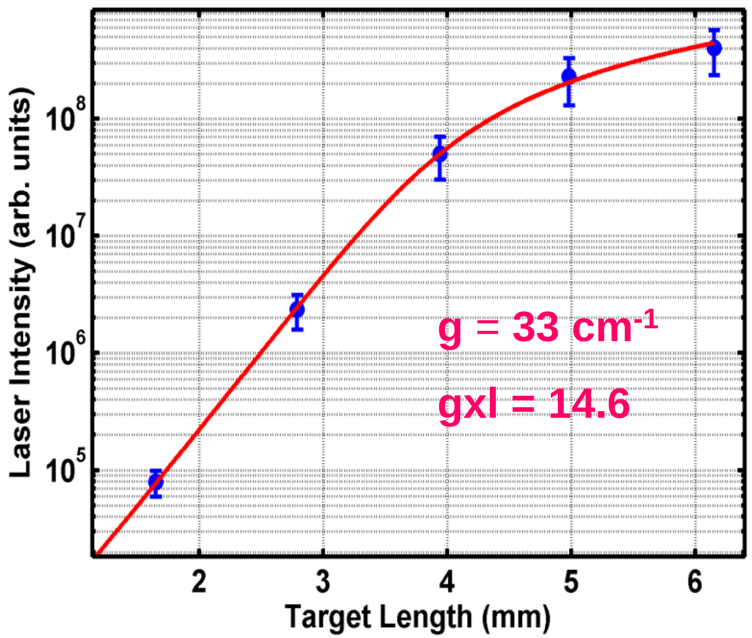
Demonstration of Gain-saturated table-top laser at 8.8 nm at 1 Hz repetition rate

Ni-like Lanthanum $4d^1S_0$- $4p^1P_1$



7.5 J Total Pump Energy

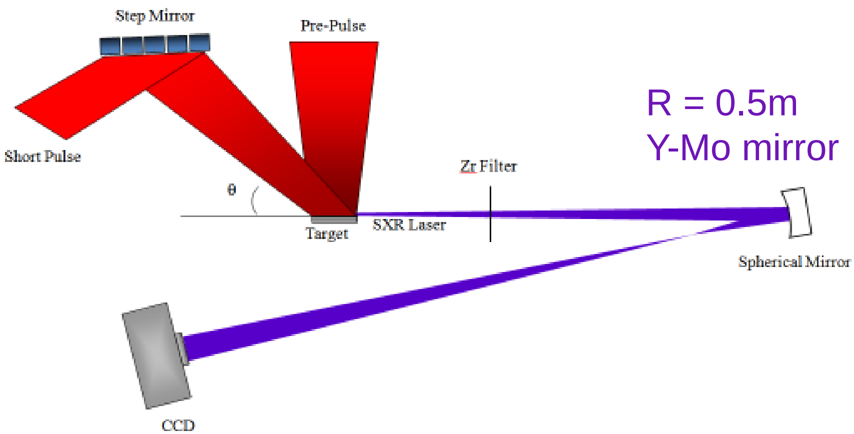
Pulse energy up to ~ 2.7 μJ

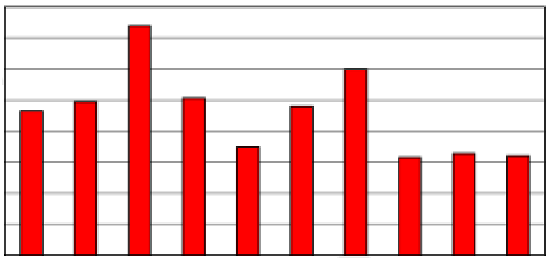


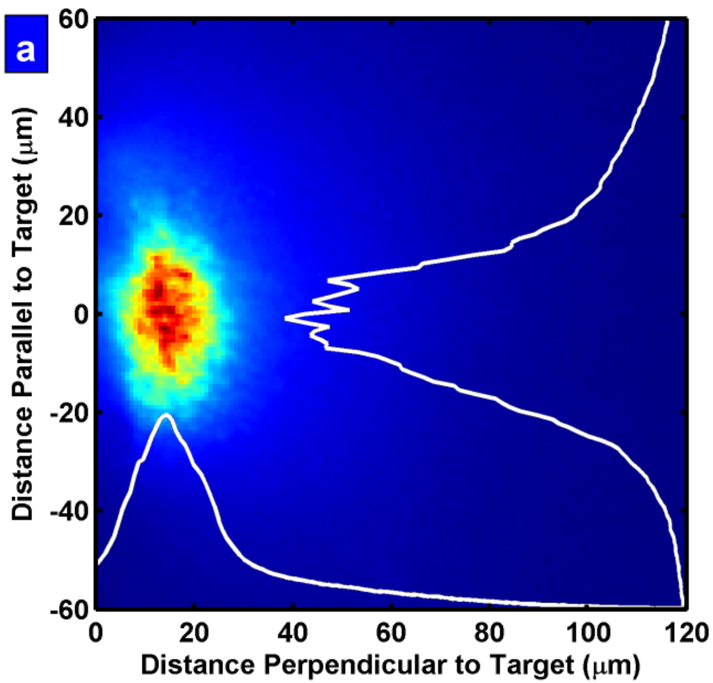
D. Alessi et al. Phys. Rev. X ,1, 021023 (2011)

1 Hz λ= 8.8 nm laser output intensity exceeds computed saturation intensity by an order of magnitude

Near field beam profile measurement







SXRL Fluence: 0.6 J cm^{-2}

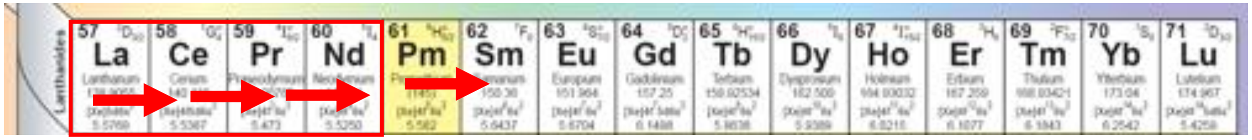
Experiment: I ~ 2.4 x 10^{11} W cm^{-2}

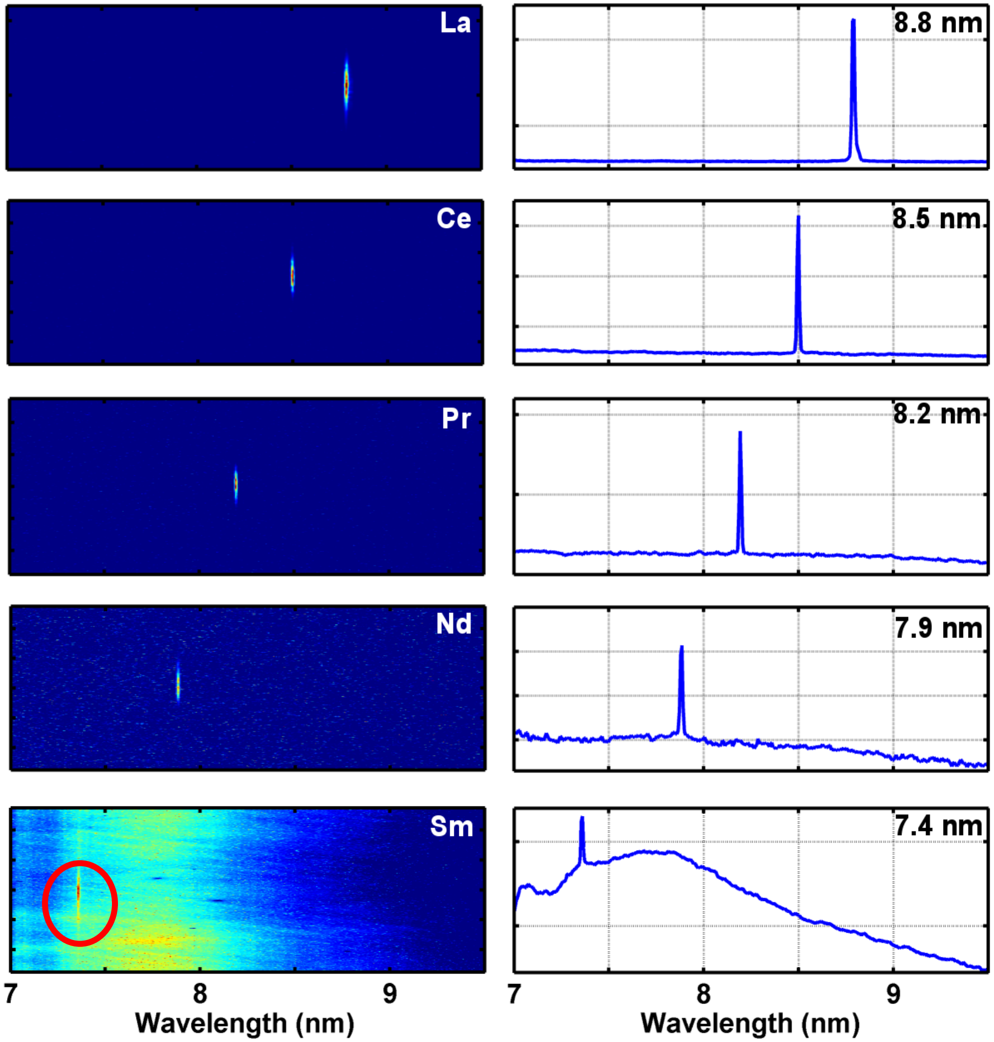
Computed I_{sat}: ~3 x 10^{10} W cm^{-2}

D. Alessi et al. Phys. Rev. X ,1, 021023 (2011)

Lasing in transitions down to 7.36 nm

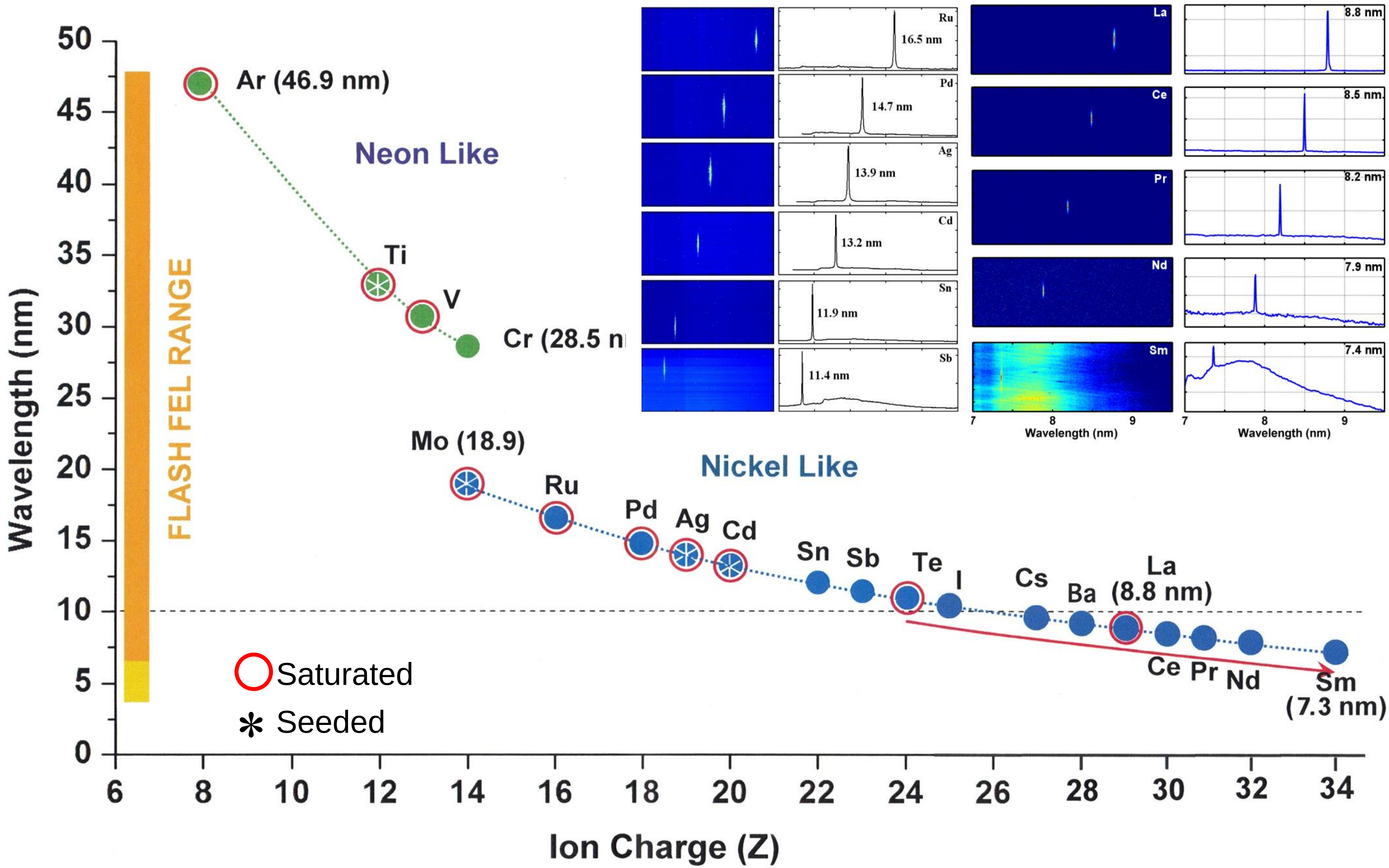
Nickel-like lanthanide ions $4d\,^1S_0$- $4p\,^1P_1$





D. Alessi et al. Phys. Rev. X ,1, 021023 (2011)

Gain-saturated table-top SXRLs cover 8.8 nm - 47 nm wavelength region

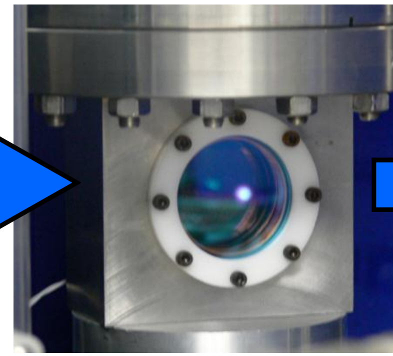


D. Alessi et al. Phys. Rev X, 1, 021023, (2011)

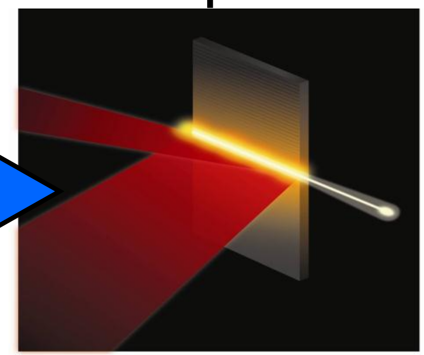
The Next Generation: Increasing the repetition rate of Table-Top Soft X-Ray Lasers to 100 Hz

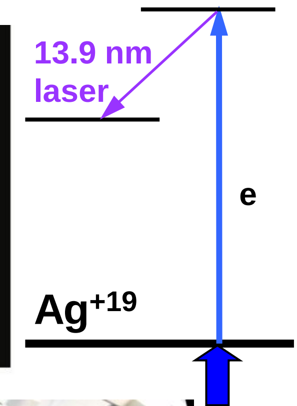
Laser Diode Drivers

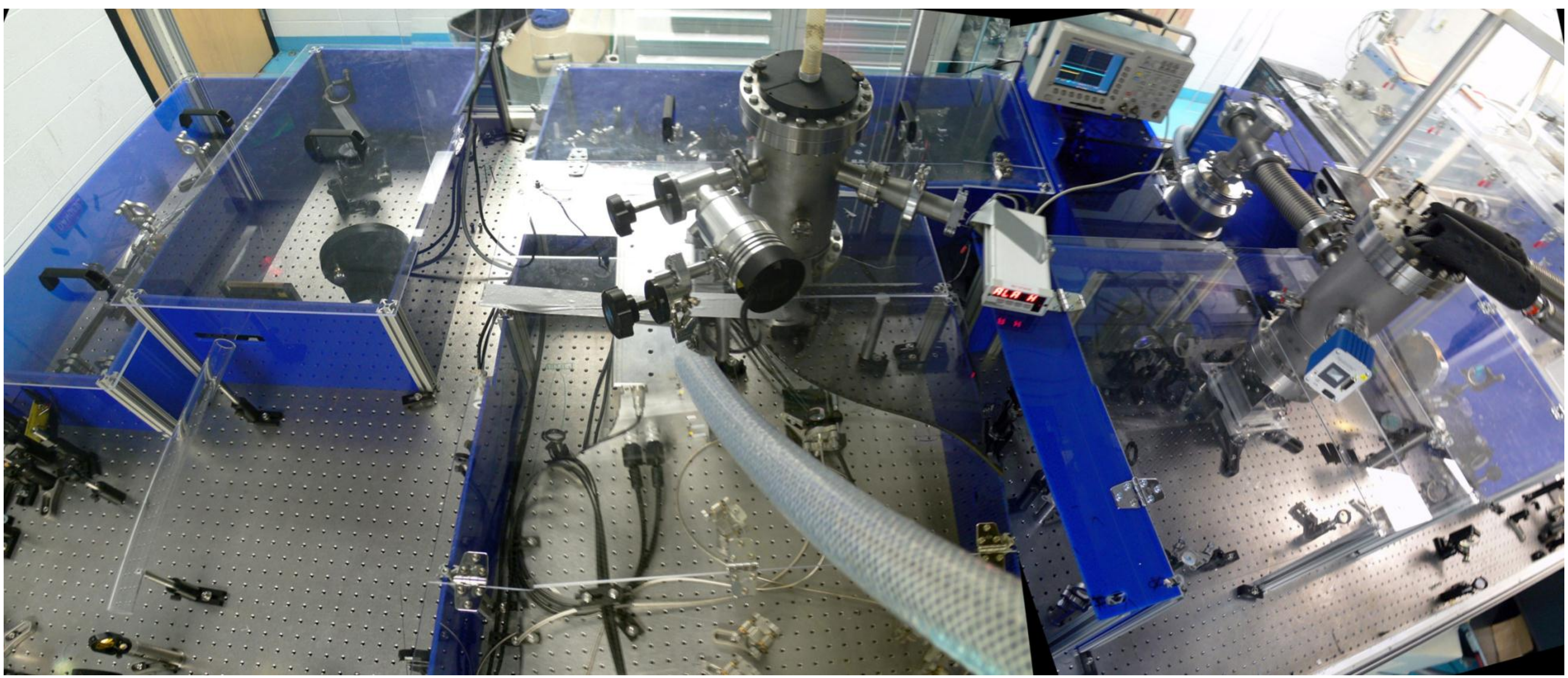
Solid State Ultrashort Pulse High Power Laser



Soft X-Ray Plasma Amplifier

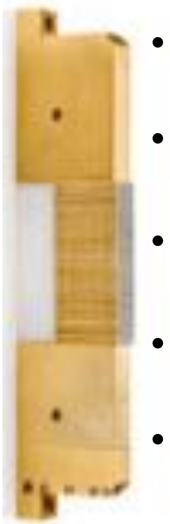






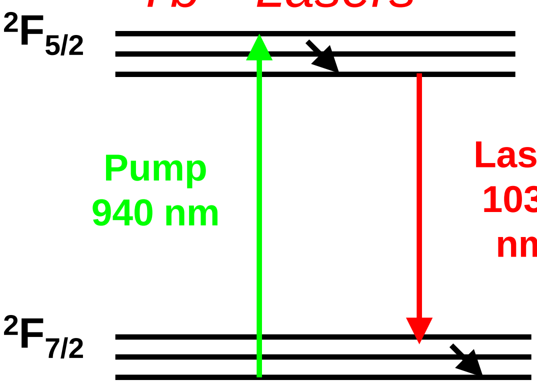
Directly diode-pumped Yb CPA laser increases repetition rate and average power

Laser Diode Pumping Advantages



- Highly efficient
  - >50% Electrical efficiency
- Narrow bandwidth
  - Efficiently pump a single transition
- Directional
  - End-pumping
- Very high average power
  - Allow high repetition rate
- Compact

Yb^{+3} Lasers

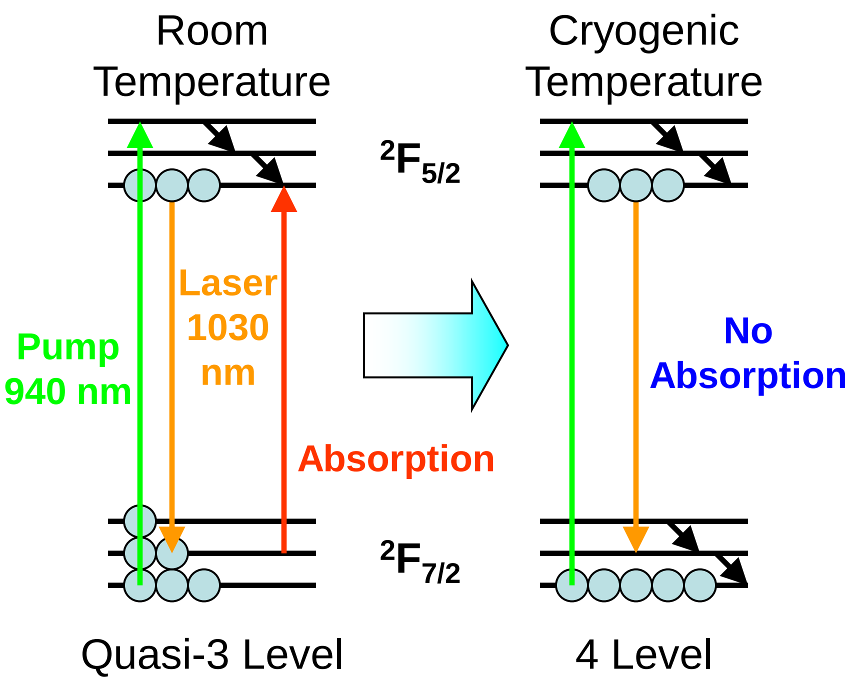


- Absorption bands at InGaAs wavelengths
- Very low quantum defect (<10%)
- Long lifetime for high energy storage

Thermal and gain properties of Yb:YAG are dramatically improved at cryogenic temperature

Yb:YAG at room and cryogenic temperature	300 K	77 K	
Thermal conductivity (W/mK)	10	90	x9
Thermo-optic coefficient (10^{-6}/K)	7.8	0.9	x1/7
Expansion coefficient (10^{-6}/K)	6.14	1.95	x1/4
Saturation fluence (J/cm^2)	9.2	1.7	x1/7

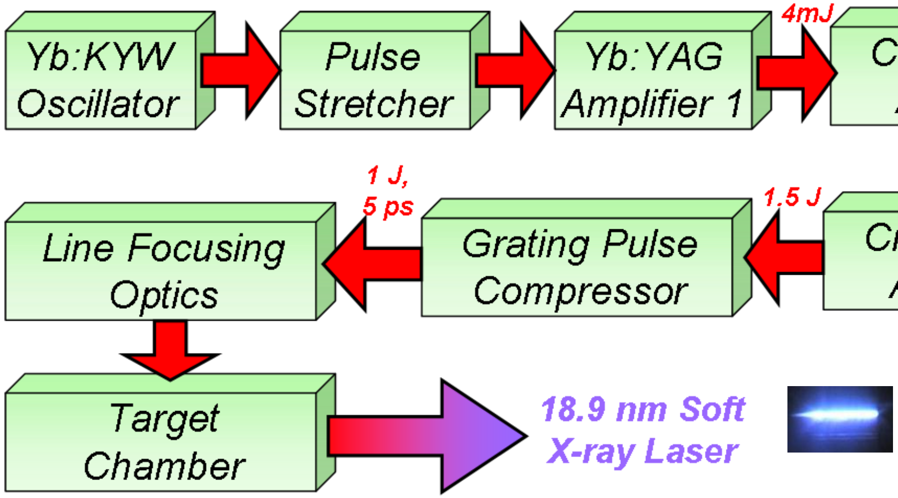
G. A Slack and D. W. Oliver; Phys. Rev. B4; 592-609 (1971)
R. Wynne, J. L. Daneu and T. Y. Fan; Appl. Opt. 38, 3282-3284 (1999)
R.L. Aggarwal, et. al., Journal of Applied Physics, 98, 103514, (2005).



Other recent cryogenic diode-pumped CPA work:

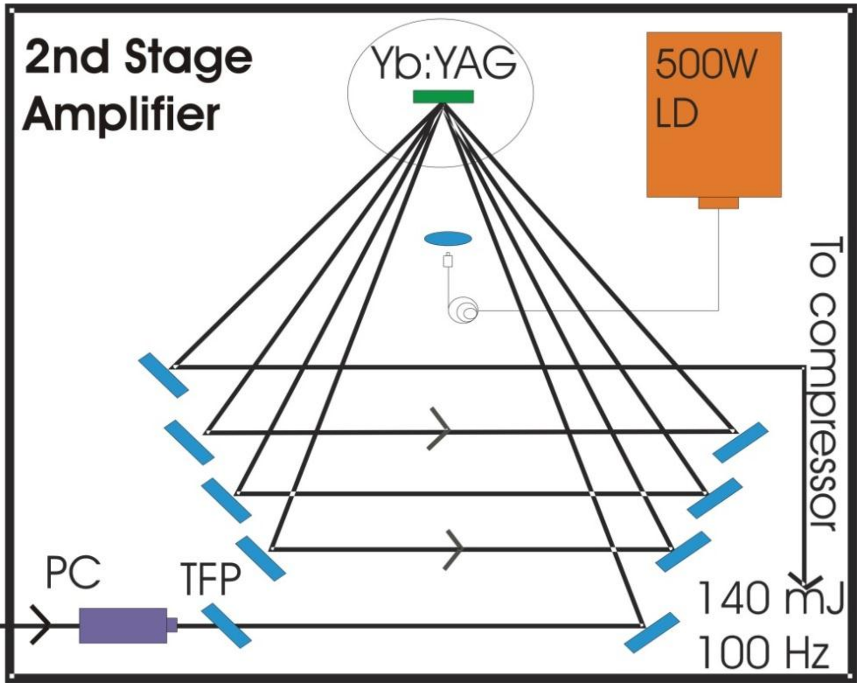
1. *K.H. Hong, et al., Optics Letters **35**, 1752, (2010).*
2. *D. Rand, et al., CM3D.4 CLEO 2012.*
3. *D.E. Miller, et al., CM3D.2 CLEO 2012.*
4. *K. Ogawa, et al., CMB.4, CLEO 2011.*

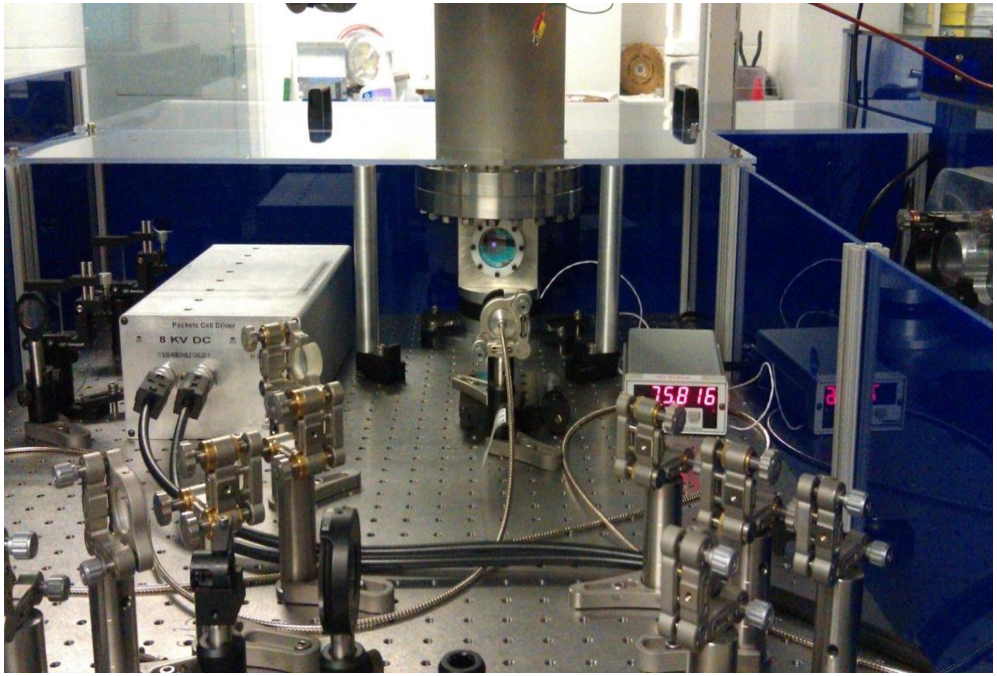
Compact high power diode-pumped CPA laser driver for 100 Hz table-top SXRL



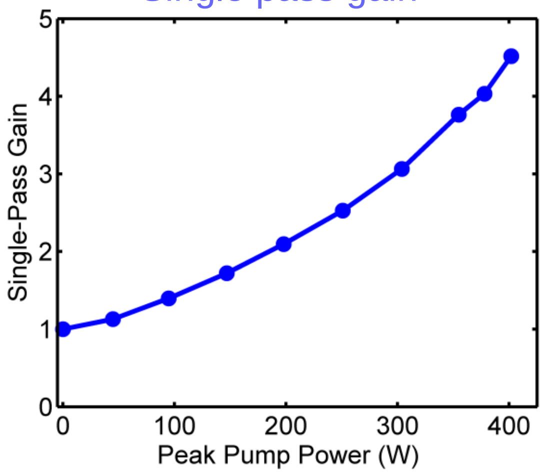
2nd stage cryo-cooled Yb:YAG amplifier

140 mJ, 100 Hz, amplifier operation demonstrated

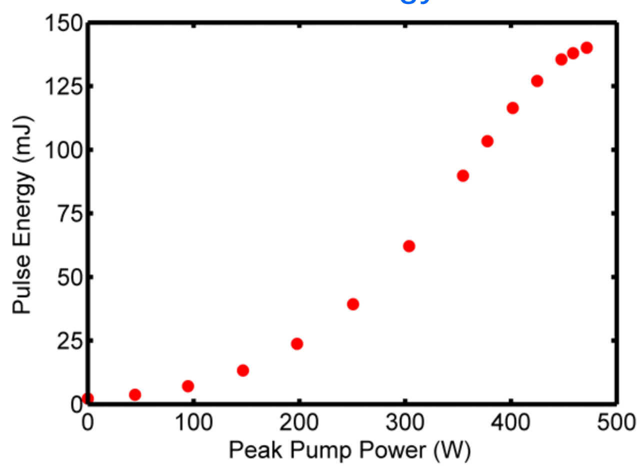




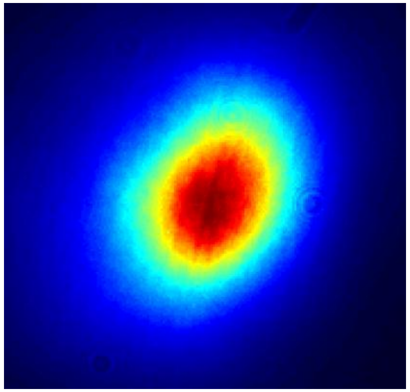
Single pass gain



Pulse energy

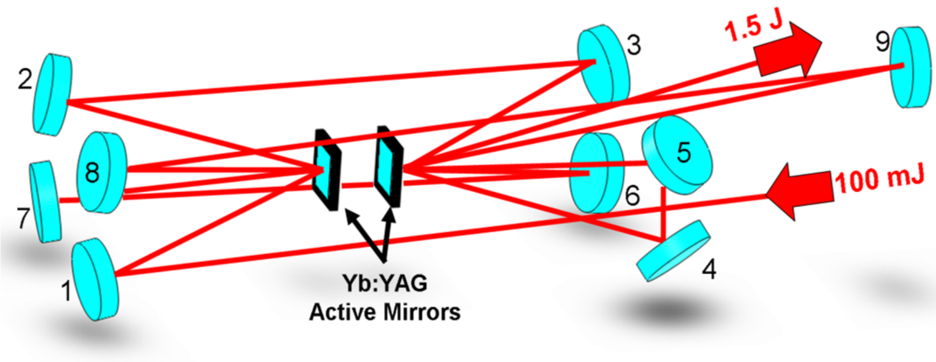


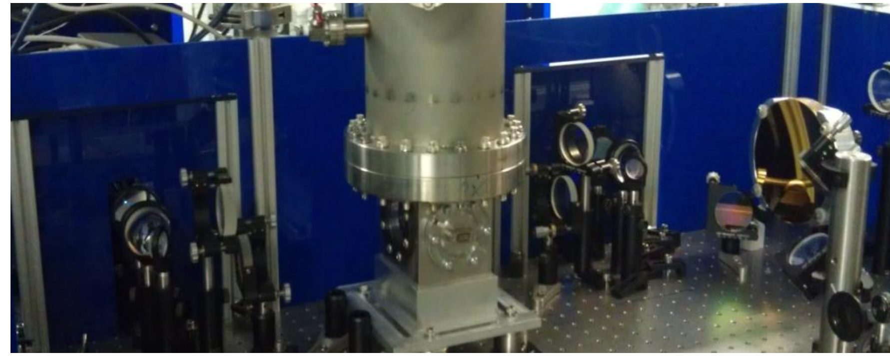
Beam pattern



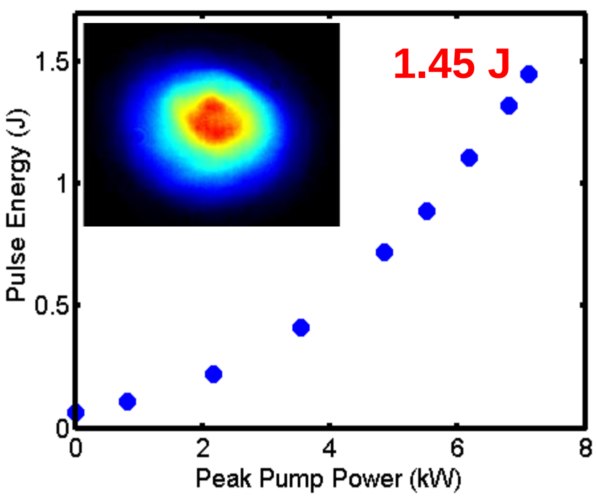
A. Curtis et al. Optics Letters, 36, 2164, (2011)

100 Hz repetition rate 1.5 Joule diode-pumped cryo-cooled Yb:YAG amplifier

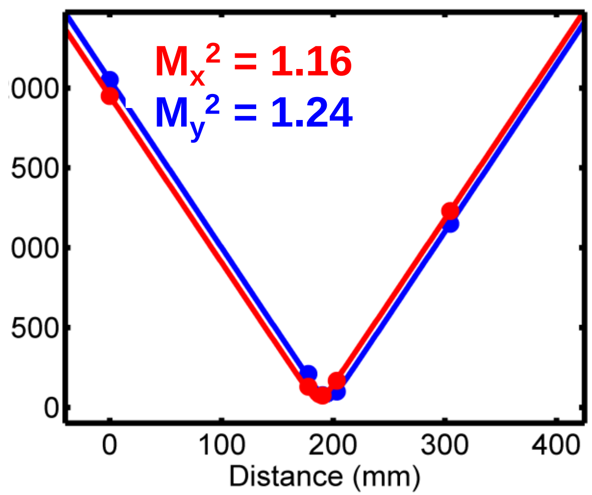




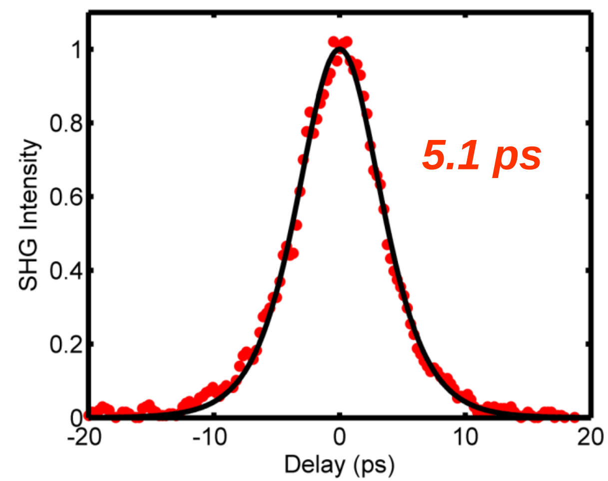
Uncompressed pulses



M^2 of amplified pulses

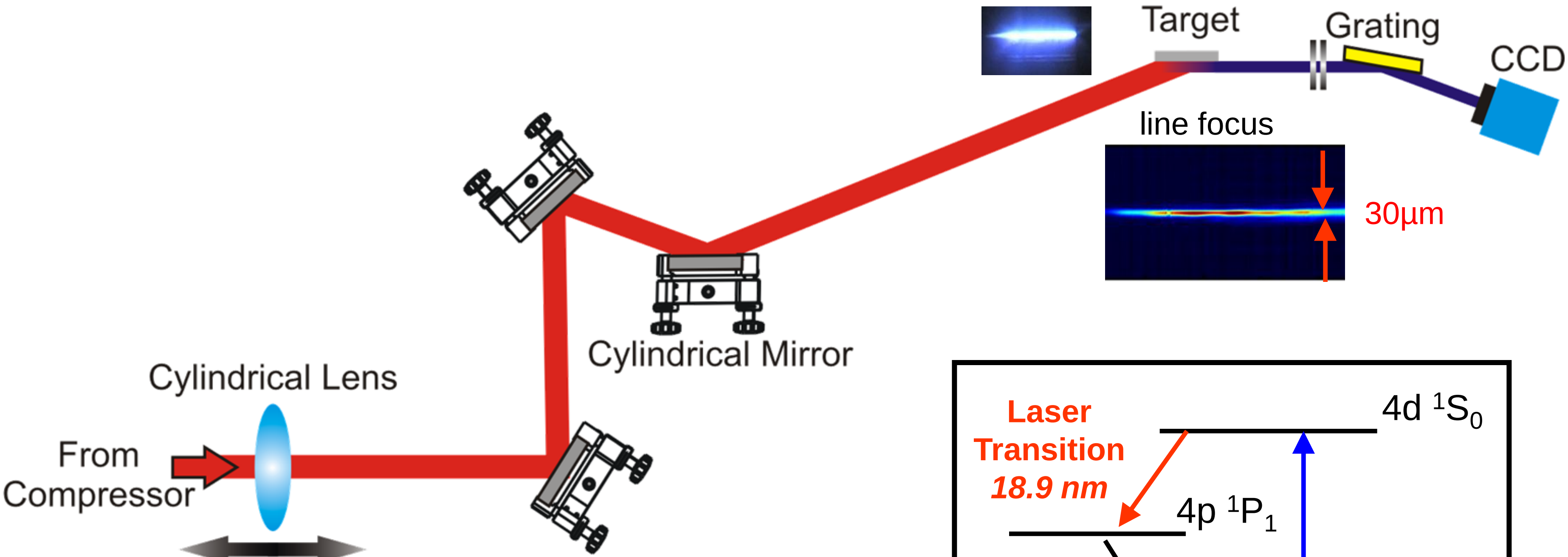


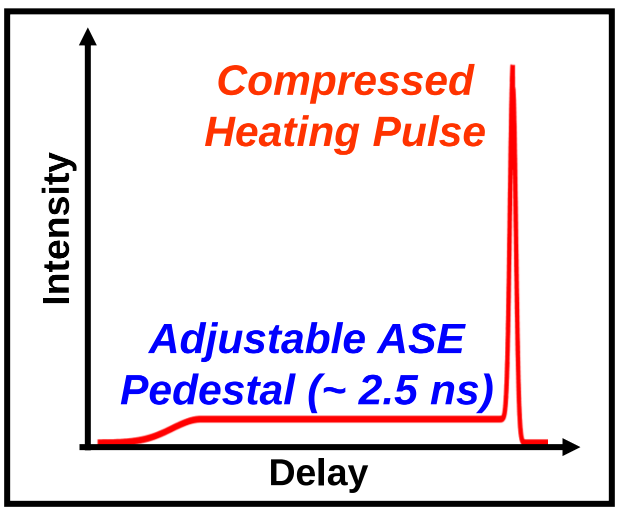
2nd order autocorrelation of compressed 1 J pulses

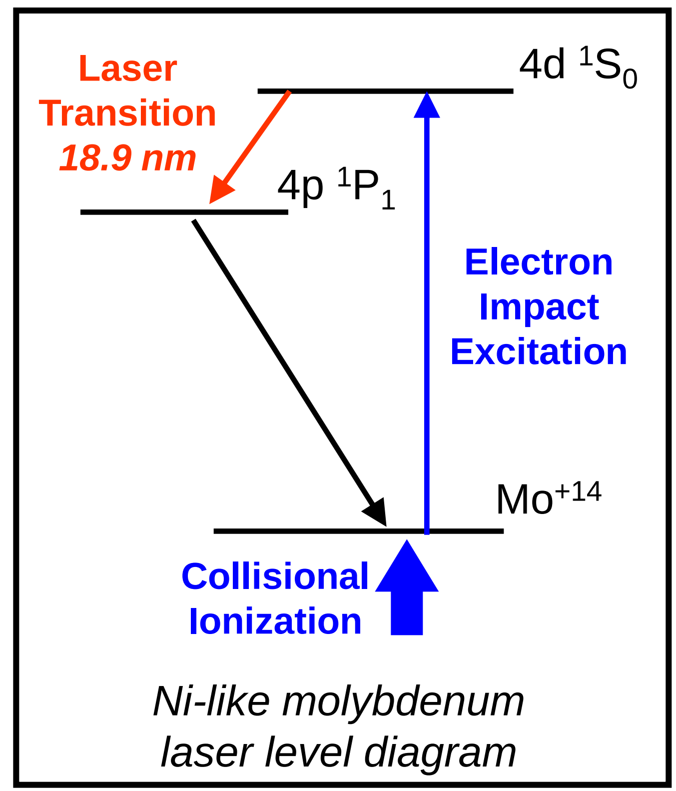


1 J, 5 ps **pulses at 100** ***Hz*** **repetition rate**

Soft X-Ray laser employs ns ASE pedestal followed by ps pump pulse from same CPA diode-pumped laser

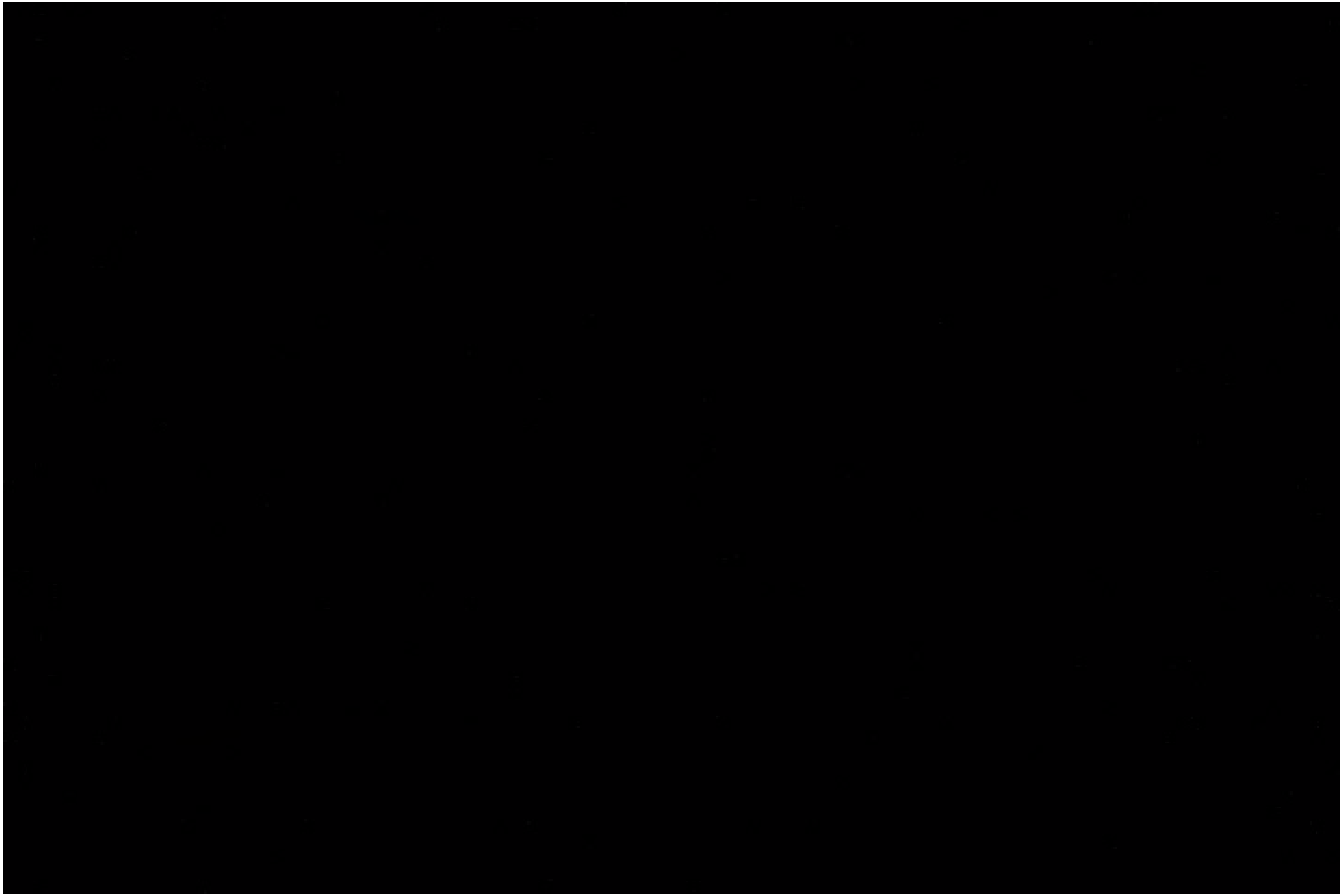






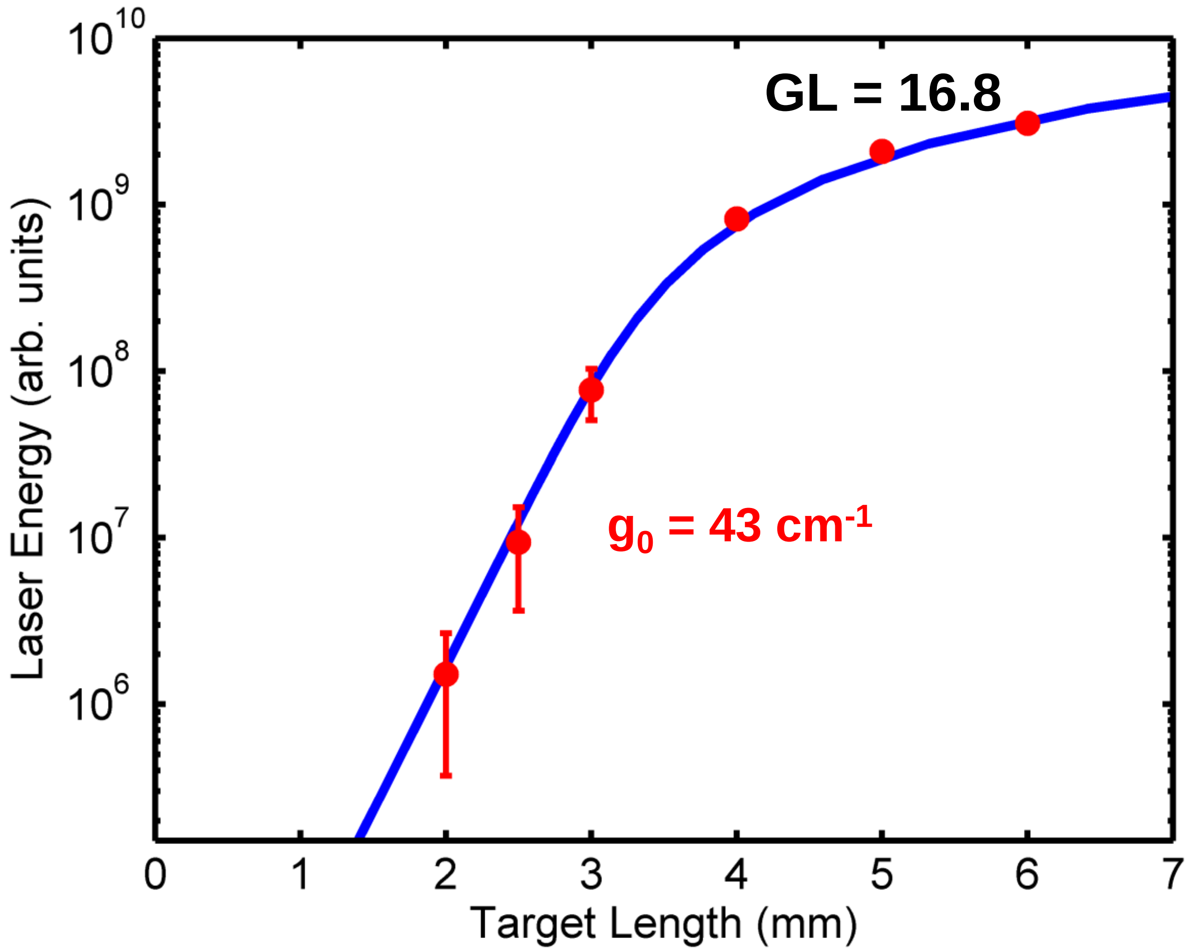
B. Reagan et al., Optics Letters (2012)

100 Hz Operation



Gain-Saturated 18.9nm Laser Operation at 100 Hz repetition rate

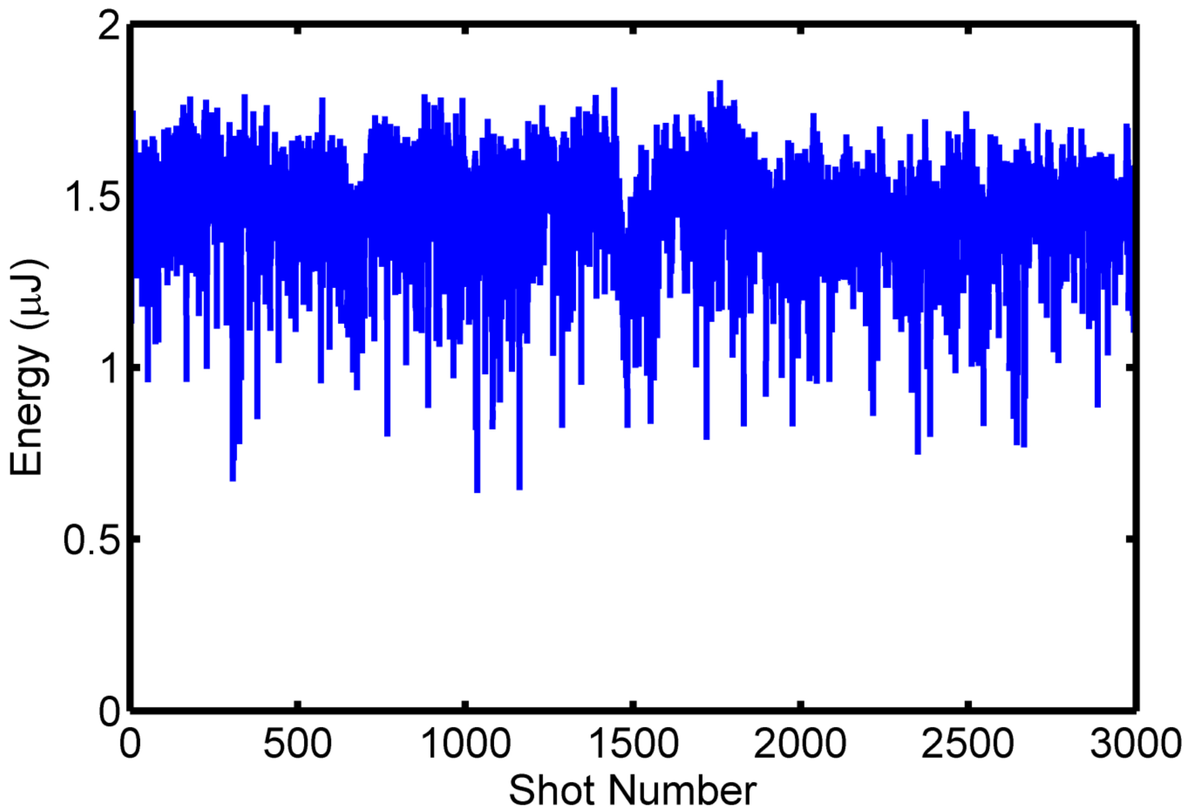
Pump: 970 mJ on target



B. Reagan et al., Optics Letters (2012)

100 Hz, 18.9 nm laser

940 mJ on target target moved at 200 um/s, (2um/shot)

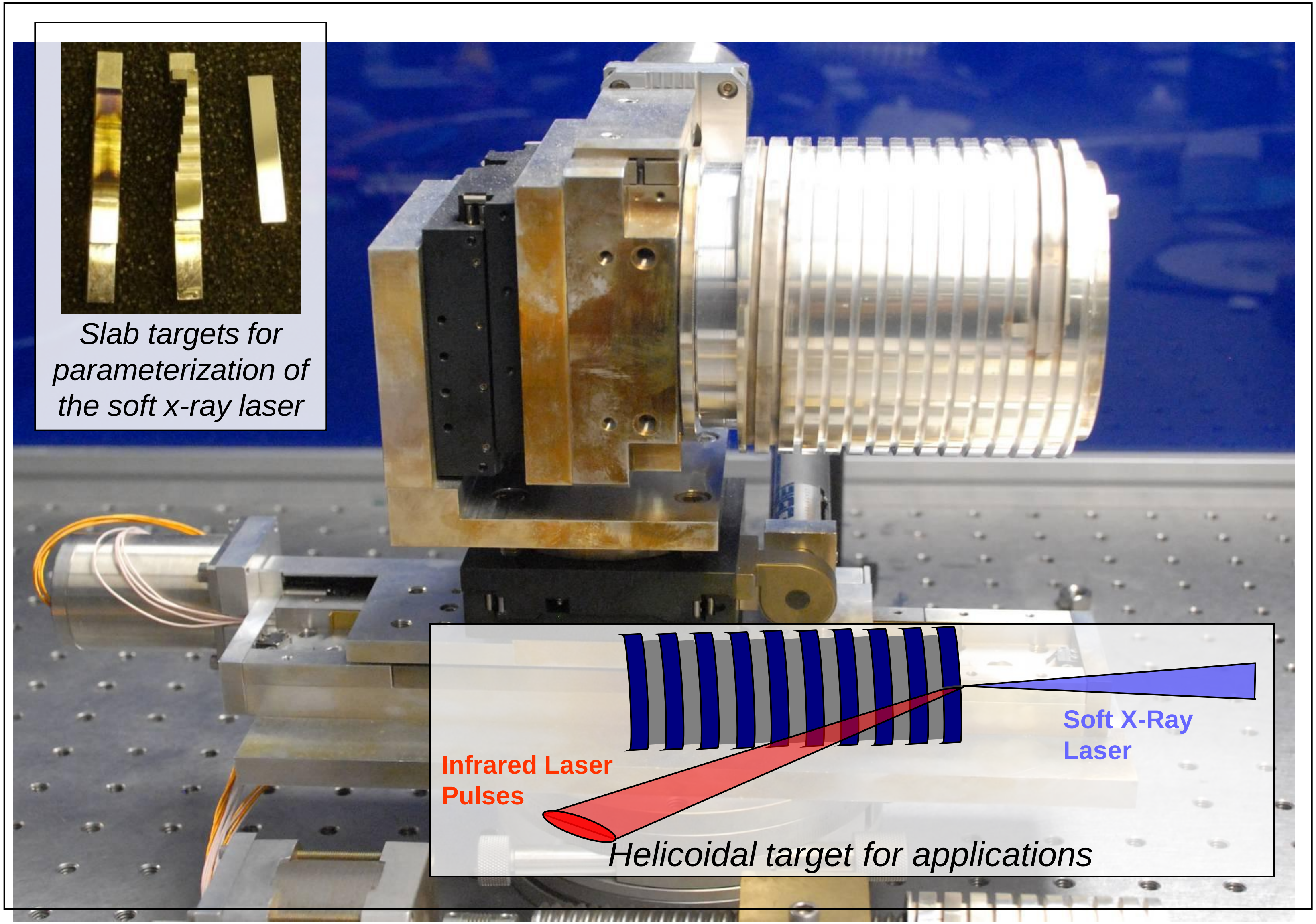


Mean Energy = 1.46 μJ, σ = 11%

0.15 mW average power

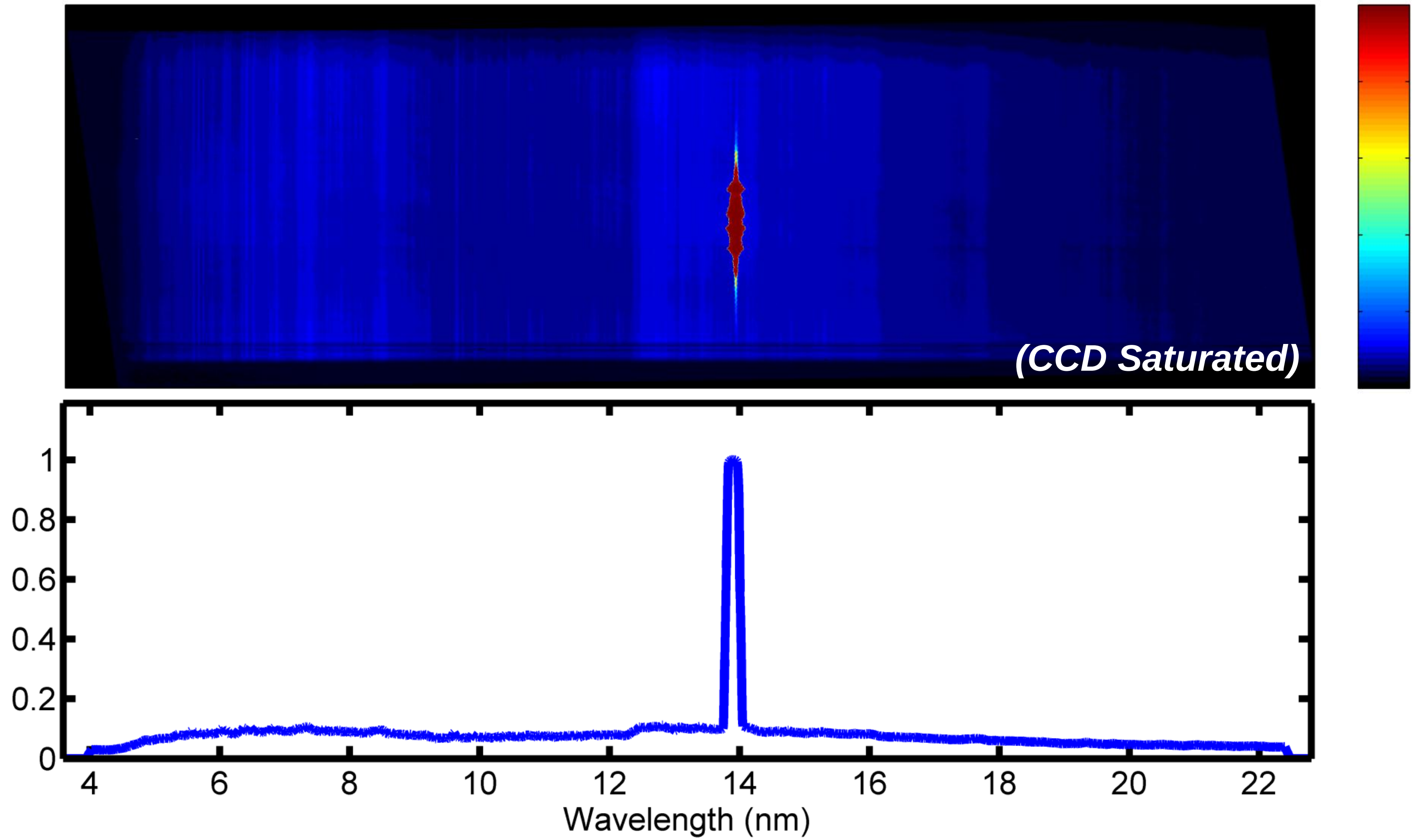
(Fermi FEL 20-65 nm: 30-60 uJ x 10 Hz = 0.3-0.6 mW Luca Giannessi ICXRL)

Helicoidal targets developed to allow continuous operation at 100 Hz repetition rate



A. Weith et al. Optics Letters, 31, 1994, (2006)

Demonstration of *all-diode-pumped laser* at 13.9nm in Ni-like silver plasma



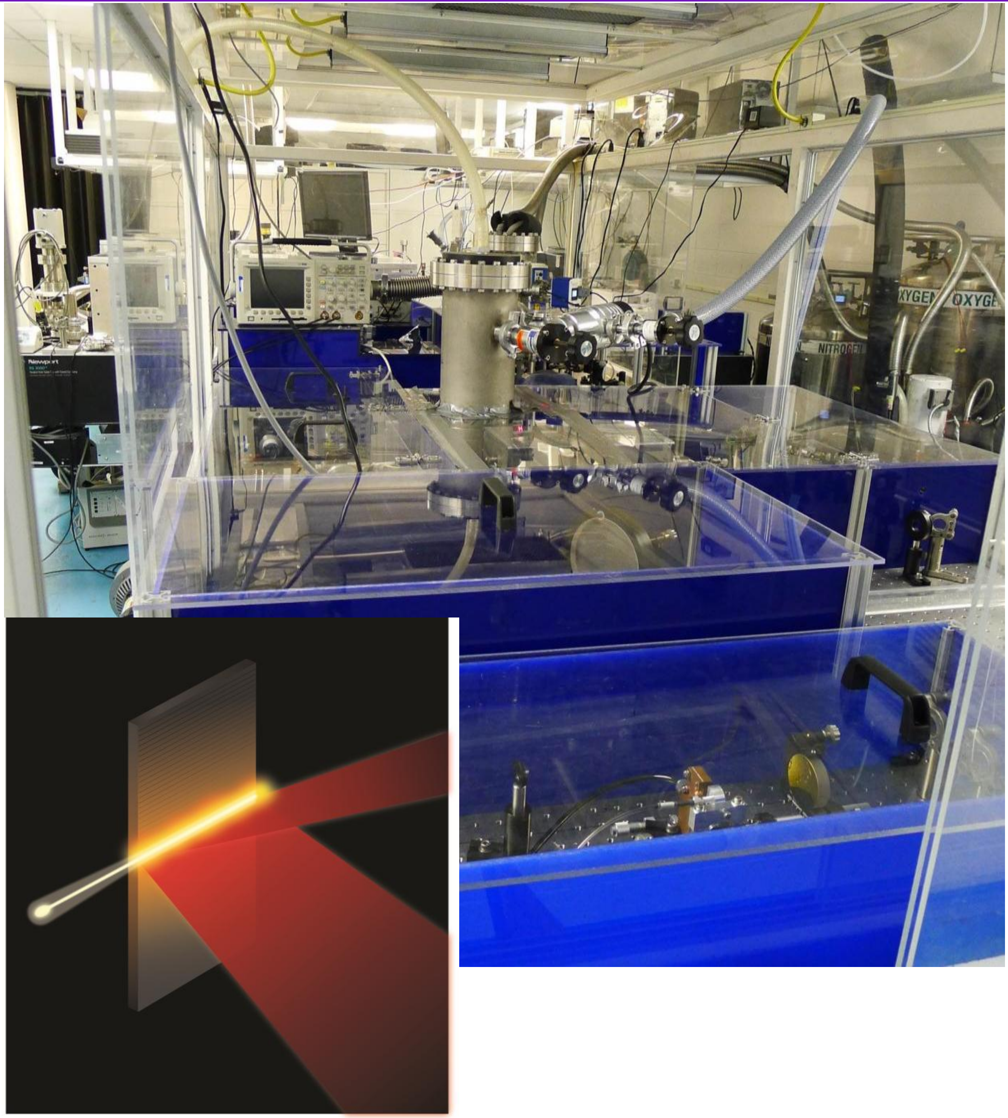
Single-shot spectrum of Ag plasma, 950 mJ pulse energy on target
Driver laser operating at 50 Hz repetition rate.

B. Reagan et al., Optics Letters (2012)

Summary

- Gain-saturated table-top SXRLs reach λ= 8.85 nm. Amplification observed down to λ= 7.3

- Compact diode-pumped soft x-ray laser operating at record 100 Hz rep. rate produces 0.15 mW average power on a table-top



Work Supported by the NSF Engineering Research Centers Program and the US Department of Energy

EUV
An NSF Engineering Research Center

Acknowledgement

Colorado State University